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USBS Acoustic Receiver Evaluation

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Abstract

McKeown, D. L., J. M. Preston and W. M. Vogel, 1991. USBS acoustic receiver evaluation. Can. Tech. Rep. Hydrogr. Ocean Sci. No. 136: vi + 44 pp.

The operational accuracies of three ultra-short baseline acoustic positioning range/bearing receivers, a Honeywell Hydrostar, a Ferranti-ORE Trackpoint II and a Nautronix ATS, were determined using an optical laser system as a standard. The three acoustic receivers are basically similar in configuration and function but there are significant differences of detail which impact upon their abilities to meet user needs.

Two different source/receiver geometries were employed. Attempts made with the acoustic source at the same depth as the hydrophone produced satisfactory comparisons against the optical laser system. An alternative geometry with the acoustic source at various depths relative to the hydrophone, while better mimicking typical operational scenarios, exhibited much larger position errors. Based on model studies, it is postulated that these resulted from an offset between the remote acoustic and optical targets which in turn was generated by wind and current drag on the line joining the two.

Based on the experiments done with the horizontal source/receiver geometry, the bearing accuracy of the Nautronix ATS receiver was found to be 0.35^{o} which is about two and a half times better than that determined for the Trackpoint II and Hydrostar. The range accuracy of the Nautronix ATS was determined as 0.49 m compared to 0.39 m for the Trackpoint II. The Hydrostar unit tested does not measure range. The Trackpoint II and Hydrostar appeared to generate acceptable fixes for about 90% of the interrogation cycles whereas the Nautronix ATS was only successful about 67% of the time.

Résumé

McKeown, D.L., J.M. Preston and W.M. Vogel. 1991. USBS Acoustic Receiver Evaluation. Can. Tech. Rep. Hydrogr. Ocean Sci. No. 136: vi + 44 pp.

Les auteurs ont évalué l'exactitude opérationnelle des trois récepteurs acoustiques de distance/cap de positionnement à ligne de base ultracourte, le Hydrostar Honeywell, le Trackpoint Ferranti-ORE et l'ATS Nautronix. Deux géométries source/récepteur différentes ont été utilisées. Les mesures prises lorsque la source acoustique était à la même profondeur que l'hydrophone ont produit les meilleurs résultats par rapport à ceux obtenus avec un système laser optique utilisé comme étalon. Une autre géométrie, dans laquelle la source acoustique était à diverses profondeurs par rapport à l'hydrophone, a donné de moins bons résultats, bien qu'elle correspondait mieux aux scénarios opérationnels typiques. On croit que le problème découle d'un écart inconnu entre la cible optique et la cible acoustique éloignée, en raison de la traînée de vents et de courants sur la ligne les unissant.

Les trois récepteurs présentent des configurations et fonctions semblables, malgré des différences de réalisation importantes, qui influent sur leur capacité à satisfaire aux besoins de l'utilisateur. L'exactitude en cap de l'ATS Nautronix avec une géométrie horizontale source/récepteur est de 0,35°, ce qui équivaut à environ deux fois et demie celle du Trackpoint et de l'Hydrostar. Son exactitude en distance est 0,49 m, celle du Trackpoint II étant de 0,39 m. L'appareil Hydrostar testé ne mesure pas la distance. Le Trackpoint et l'Hydrostar semblent produire des mesures acceptables pour environ 90% des cycles d'interrogation, tandis que l'ATS de Nautronix n'a produit des mesures correctes que 67% du temps.

1. Introduction

The position of Remotely Operated Vehicles (ROV's), towed bodies and sample sites relative to a vessel can most conveniently be determined with an ultra-short baseline system (USBS) acoustic positioning receiver. A number of commercial USBS receivers exist. In order to select the most appropriate one for a particular task and to interpret the positioning information obtained, a knowledge of system accuracy is required. While one or more trials of this nature are known to have been carried out (Anon. 1990), the results do not appear to have been published. Independently and approximately simultaneously, staff at both the Bedford Institute of Oceanography (BIO) on the Atlantic Canadian coast and at the Defence Research Establishment Pacific (DREP) on the Pacific Canadian coast decided to determine the operational accuracy of several commercially available USBS receivers. At BIO a comparison of the Nautronix ATS, the Ferranti-ORE Trackpoint II and the Honeywell Hydrostar was planned. At DREP only the first two were to be tested. Neither field trial was intended as an exhaustive test of receiver accuracy and capability. Instead, the objective was to determine in quantitative terms some measure of comparative performance of the receivers under simulated realistic operating conditions.

Very accurate laser range-bearing systems were employed as standards against which the positioning accuracy of the USBS receivers were compared. Because the acoustic signals propagate through a water path while the optical signals must pass through an air path, the acoustic and corresponding optical units at each end of the meausrement path lie on opposite sides of the air/water interface. This leads to two possible experimental geometries: 1) rigidly connect the optical prism above the sea surface with an acoustic transponder beneath it; or, 2) suspend the acoustic source on a flexible line at some depth beneath a buoy on which the optical prism is mounted. The former limits the source-receiver geometry to a horizontal plane whereas the receivers were all designed for optimum performance with near vertical geometry. The latter permits experimentation in a more suitable vertical source/receiver geometry but introduces the potential of winds and currents causing significant horizontal displacement of the acoustic target relative to the optical one with a consequent degredation in the validity of the position comparison. Quite fortuitously, BIO selected the first approach and DREP the second.

During the data collection phase, the authors became aware that their objectives were similar and their experiments were complementary. Therefore, it was agreed that the data sets would be merged and analyzed as a single entity. Both experimental set-ups are described below. The characteristics of each receiver are examined, the range and bearing error data sets for each are summarized and conclusions are drawn concerning the operational performance of each.

2. USBS Receiver Technology

2.1 Generic Features of USBS Receivers

Ultra-Short Baseline System (USBS) receivers are characterized by a single underwater hydrophone which contains an array of acoustic transducers spaced a fraction of a wavelength apart. The direction of the acoustic source with respect to the hydrophone is deduced from a measurement of the phase of the acoustic signal as it traverses across this array. Range is normally determined from a measurement of the transit time of the acoustic signal between the source and the hydrophone, the difference between their depths and a knowledge of the speed of sound over the path.

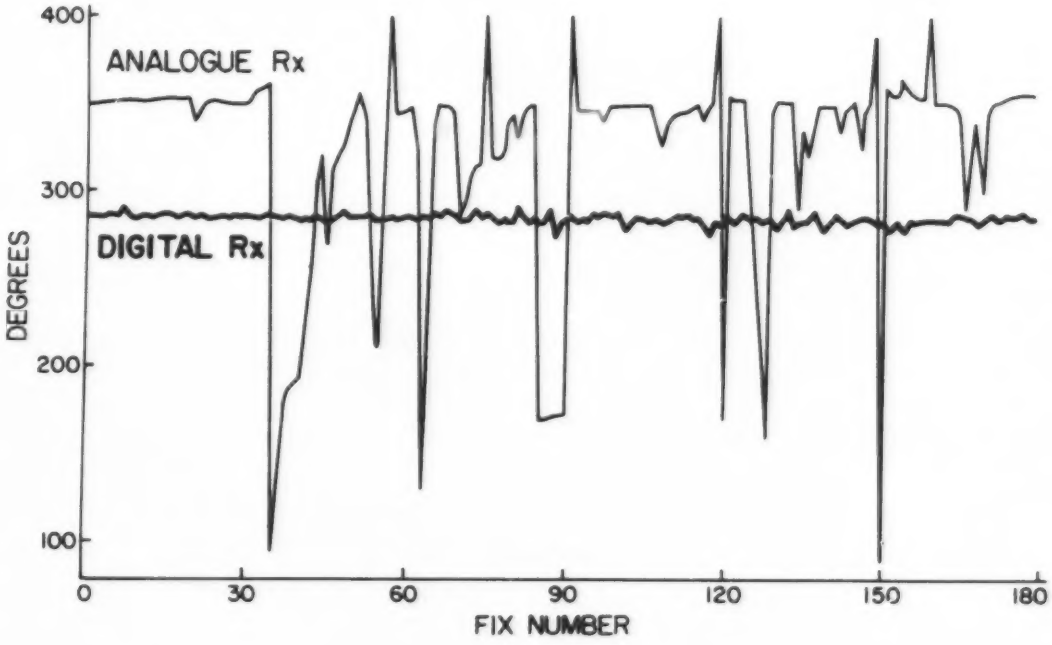


Figure 1. Relative bearing of a source as measured with an old style analogue USBS receiver and a modern digital one.

Until the mid-70's, the signal processing and computational technologies in USBS receivers were analogue in nature. Typically, they exhibited unacceptably poor performance (McKeown, 1984). With the advent of modern digital signal processing methodology and the explosive growth of microprocessor computational capability, a new generation of USBS receivers exhibiting greatly improved performance came on the market. Figure 1 illustrates the comparative performance of these two

technologies. The time series illustrated were collected some years apart but at the same location and under very similar conditions.

Typically a USBS receiver consists of three major components: 1) an acoustic transceiver, a computer and video display contained within a single case with a front panel keypad for operator control; 2) an underwater unit incorporating a hydrophone and transmitting and receiving electronics; and 3) an interconnecting cable. Some systems incorporate a set of tilt sensors in the hydrophone case and others place them in a separate package referred to as a Vertical Reference Unit. The bearing measurements are made relative to the plane of the hydrophone face. Information from the tilt sensors is used to translate this to a relative bearing in the operator's horizontal reference plane. They generally are capable of tracking two or more free-running pingers, responders or transponders simultaneously.

The operator can control certain receiver operations and display formats via a menu system activated by a keypad and/or pointing device. These permit the operator to change parameters such as threshold levels on incoming signals, filtering or averaging of the computed positions, hydrophone and source offsets in all three coordinates and average sound speed used for range computations. They also facilitate changing the range scale, the number of targets being tracked and other display characteristics. In addition to the presentation of the positions on an integral graphics display, the receivers permit the attachment of remote displays and logging devices.

2.2 Honeywell Hydrostar

Of the three receivers tested, the Honeywell Hydrostar (Beaton, 1983, McKeown, 1990) employs the oldest microcomputer technology dating from the mid-70's. It uses an Intel single board computer for position computation and its monochrome block graphics display now appears quite dated. Nevertheless, as will be seen below, its positioning performance is quite comparable to more modern receivers. The actual receiver tested was purchased in 1983 from Honeywell although the units are now manufactured by Nautronix Ltd. As delivered, it was capable only of tracking a pinger operating at a precisely controlled repetition rate. It has subsequently been updated to track responders but is incapable of tracking transponders, although the latest versions do. The operating frequency range is 22 to 30 kHz. The manufacturer only specifies positioning accuracies for acoustic sources within 45^{o} of the vertical but indicates that the unit will function at shallower depression angles with reduced accuracy.

The operator has only limited control over the receiver configuration. To position an acoustic source, he need do little more than define its transmission characteristics. He can also attempt to improve performance by altering the signal threshold

level and apply smoothing to the computed positions. Unfortunately, the receiver provides virtually no diagnostic information to assist in this endeavor.

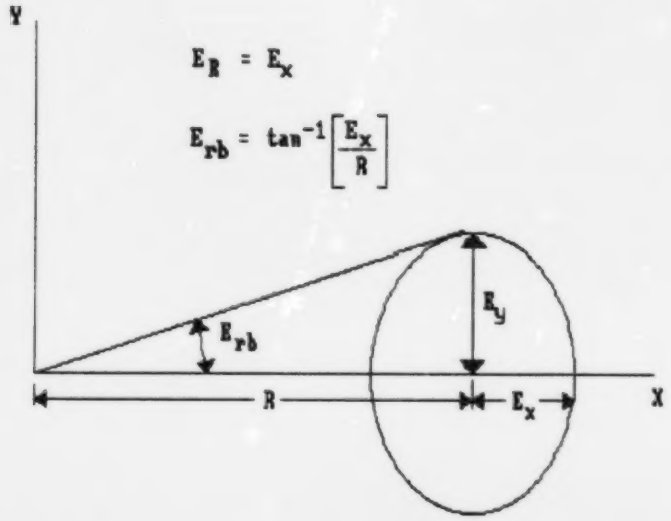


Figure 2. Schematic representation of USBS receiver range error (Er) and relative bearing error (Erb) relative to a postulated position error (Ex).

The manufacturer initially specified the positioning accuracy of the Hydrostar as:

a) 1.6% of slant range at horizontal offsets half the source depth (50% offset);
b) 2.9% of slant range at horizontal offset equal to source depth (100% offset).

The specification did not explain how this position error translated into a range error (Er) and a relative bearing error (Erb). If it can be interpreted as illustrated in Figure 2, then it translates to bearing inaccuracies of $+/-0.92^{o}$ and 1.66^{o} respectively. Subsequent to the purchase of this receiver, the manufacturer revised the specification to $+/-0.40^{o}$ at 50% offset. While the corresponding error at 100% offset was not given, one can infer from the earlier specification that it will probably be in the order of $+/-0.72^{o}$. For near horizontal geometry, that is, source and receiver at similar depths, the only bearing accuracy information provided by the manufacturer is that "in the pinger mode, accuracies are limited".

2.3 Ferranti-ORE Trackpoint II

The Ferranti-ORE Trackpoint II USBS receiver (Selman, 1985) is representative of early-80's microprocessor technology. Its colour graphics display and wealth of software features selectable via nested menus are a distinct operational improvement over the Honeywell Hydrostar. The unit tested operated in the 22 to 30 kHz range. Other options are 8 to 14 kHz and 28 to 40kHz. While it is capable of positioning pingers, it is usually used to locate responders and transponders. Within 45^{o} of the vertical, it computes horizontal range from the measured slant range and elevation angles. Nearer the horizontal, it uses measured slant range and telemetered or manually entered source depth to compute horizontal range. In the vicinity of 45^{o}, hysteresis is employed to smooth the transition from one algorithm to the other. Trackpoint II accuracies determined herein are based upon data obtained using a Model 4410B receiver, a Model 4610B hydrophone and version 5 software. Some data was obtained using a newer receiver incorporating version 7 software and improved calibration procedures (Anon., 1989 and Selman, 1990) but, because of postulated acoustic refraction problems, reliable conclusions could not be drawn.

One very attractive feature of the receiver is its visual and audible outputs of the incoming acoustic signal. The operational usefulness of this is far from trivial. During normal operations, the operator quickly notes any abnormality in receiver behavior when the pattern of the audible signal changes. The visual indication of transmitted and received signals as displayed on front panel LED's is very useful while attempting to track down the cause of positioning system problems. With these audible and visual cues, it is often possible to improve performance by adjusting parameters such as signal threshold level. Another useful feature of the current software is that, whenever operating parameters such as hydrophone offsets are changed or when the operator requests it, this setup information is transmitted to external logging devices.

The manufacturer specifies the range accuracy as +/-0.5 m and the positioning accuracy as 0.5% of slant range. If this is again interpreted as shown in Figure 2, the relative bearing accuracy is in the order of $+/-0.28^{o}$.

2.4 Nautronix ATS

The Nautronix ATS receiver (Zaknich, 1989) employs late '80's microcomputer technology. Its graphics provide the highest degree of resolution and there are a wide variety of colours and shapes available to mark features on the screen. The Nautronix ATS receiver tested operated at a slightly lower frequency range than the other two, namely 15 to 18 kHz. These receivers employ acoustic sources which emit a train of eight individual linear

sweeps or "chirps". Presumably this is done in order that digital signal processing techniques such as matched filters and/or correlation detection can be employed to improve operation in high ambient noise conditions and at long ranges.

The Nautronix ATS has many optional features which are not present in the other two receivers. For example, the past position history of each of the sources being tracked is displayed on the screen whereas the other two units only display the most current position. Also, a remote unit having independent control over the graphics presentation can be attached in contrast to the other two which only permit the remote display to mimic that appearing on the master.

The receiver retains operator-entered hydrophone and source offsets even when turned off. These offsets are applied to both the displayed and externally logged positions. Offsets entered incorrectly or inadvertently retained from a previous operation may not be noticed although they may be large enough to seriously affect the computed positions. Unless these offsets have been carefully recorded manually elsewhere and preserved, the data cannot later be corrected. The possibility is not a hypothetical one. It happened during the course of the trials to be described below and posed a substantial problem when the data were analyzed. The authors view this as a serious weakness requiring the prompt attention of the manufacturer.

The manufacturer specifies the positioning accuracy as 0.25% of slant range in both X and Y coordinates. Again interpreting the latter as shown in Figure 2, the relative bearing accuracy is in the order of $+/-0.14^{\circ}$.

3. Positioning Errors

Three dimensional positioning receivers of the type being considered here, suffer from range, bearing and depth error sources which are independent of each other. The range error introduces an uncertainty along the radial joining the acoustic source or target and the receiver hydrophone. The bearing error causes a position uncertainty to either side of this radial. Its magnitude is the range multiplied by the tangent of the bearing error. The depth error affects the position in the vertical plane. This report addresses only those positioning errors present in the horizontal plane and ignores that in the vertical or depth plane.

Unfortunately, acoustic USBS receiver manufacturers are not always in agreement as to how these range and bearing errors should be defined (Selman, 1989). One method of objectively quantifying them is to compare the ranges and bearings as determined by the receiver in question versus a standard system which is at least an order of magnitude more accurate. If the error distribution for a large number of such comparisons tend to congregate about a mean value then the standard deviation of the errors serves as a useful comparative measure of receiver performance.

The end user is often more interested in the overall uncertainty of a position rather than the errors in its component parts. At close range, the position error is usually dominated by the range error. At long ranges, the bearing error tends to dominate. In all cases, the combination of the range and bearing errors at any particular range describe an elliptical area of uncertainty about the defined position. The convention in the non-acoustic positioning community is to describe this position error in terms of the radius of a circle within which a certain percentage of total fixes reside (Harre, 1990).

Two such error circles, the "distance Root Mean Square" (dRMS) and the Circular Error Probable (CEP), have been defined (Harre, 1990). To be rigorously correct, the concept of dRMS is only applicable if the error distribution is Gaussian, a requirement not shared by the Circular Error Probable descriptor. Most practioners of navigation and positioning error studies utilize the CEP concept. Harre defines two different radii, CEP66 and CEP99. The former encompasses 66% of the fixes and corresponds approximately to a one standard deviation error (1dRMS). The latter encompasses 95% of the fixes and corresponds approximately to a two standard deviation error (2dRMS). The CEP radii are a function of range thus position errors which characterize different receivers can only be compared if the data sets have been collected at approximately the same ranges.

4. The Optical Positioning Systems

4.1 The Atlas PolarFix Optical Positioning System

The positioning standard used for the BIO experiments was an Atlas PolarFix Laser range/bearing (polar) measuring system. It has been used worldwide for some years for high precision hydrographic surveys. The manufacturer specifies its accuracy as:

range +/-0.1 m/km
bearing
static +/-0.015°
dynamic +/-0.025°

Harre (1990) has determined that this specification is conservative by a factor of 2 to 3. He found the corresponding position error, the CEP66 radius, to be 0.13 to 0.20 metres for ranges of 150 to 2000 m.

The system uses a laser mounted on a servo-controlled platform to track a remote passive optical reflector or prism. Its maximum horizontal tracking rate is +/-10° per second which is well beyond the limit required to track a moving ship. It applies a predictive filter to a set of the most recent measured positions of the remote prism in order to compute its position as of the instant that information is sent to an external logging device. The unit continuously and automatically tracks the remote prism producing fixes at a rate of about 3 per second.

4.1 The Esprit Laser Ranger

The positioning standard used for the DREP experiments was an Esprit Laser Ranger range/bearing (polar) measuring system. It is similar in principle to the Atlas PolarFix except that the operator must track the prism manually using a built in telescope. The manufacturer states that the range accuracy of this unit is 0.25 m or 0.05% of range, whichever is greater and the bearing accuracy is 0.01°. During these experiments, the operator annotated the logged data whenever the laser system was properly tracking the target and only data obtained during these periods was analyzed. At the end of each data run, it was verified that the reference direction of the system had not changed.

5. The Experimental Geometries

5.1 The BIO Experiment

The BIO experiments took place in Bedford Basin, a 2 by 3 mile embayment inshore of Halifax harbour on the Atlantic Ocean. Water depth at the site was about 41 m. The hydrophone was suspended 3 m below the surface on a rigid pole which was clamped to the side of the Defence Research Establishment Atlantic's acoustic calibration barge. This large barge had a draft of

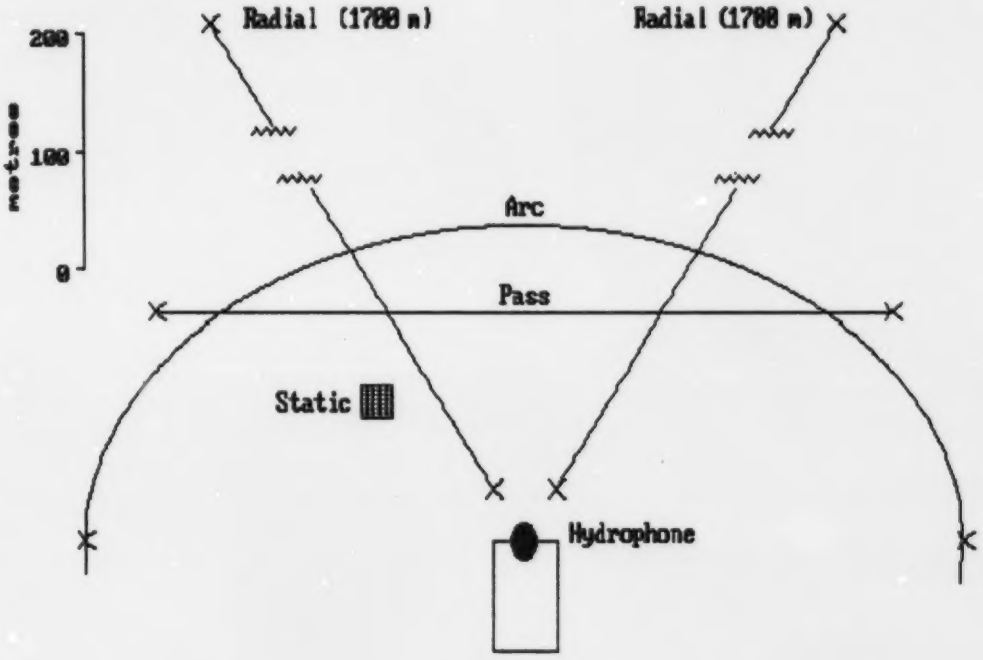


Figure 3. Schematic representation of the hydrophone position (H) relative to the source during the RADIAL (R), ARC (A), STATIC (S) and PASS (P) maneuvers.

0.9 m and was secured on a four point mooring. The laser sensing head of the Atlas PolarFix laser range/bearing system was mounted immediately above the hydrophone. The acoustic source being tracked was secured 3 m beneath the surface on a vertical pole attached to the side of a workboat. The laser tracking system's optical prism was secured to the top of this pole. No attempt was made to align the reference directions of the acoustic and optical system. Instead, an adjustment was made for the fixed bearing offset between them during analysis.

The workboat steamed directly away from the barge on a constant headings then returned on the reciprocal to produce comparative optical and acoustic data sets of constant bearing and varying range (Figure 3). These data sets will be referred to as

"RADIAL" in the following discussion.

The workboat traversed an arc of circle at various ranges from the barge in order to generate data sets of varying bearing and constant range (Figure 3). These data sets will be referred to as "ARC" in the following discussion.

The workboat remained at approximately a constant location relative to the barge to create data sets of nominally constant range and bearing (Figure 3). These data sets will be referred to as "STATIC" in the following discussion.

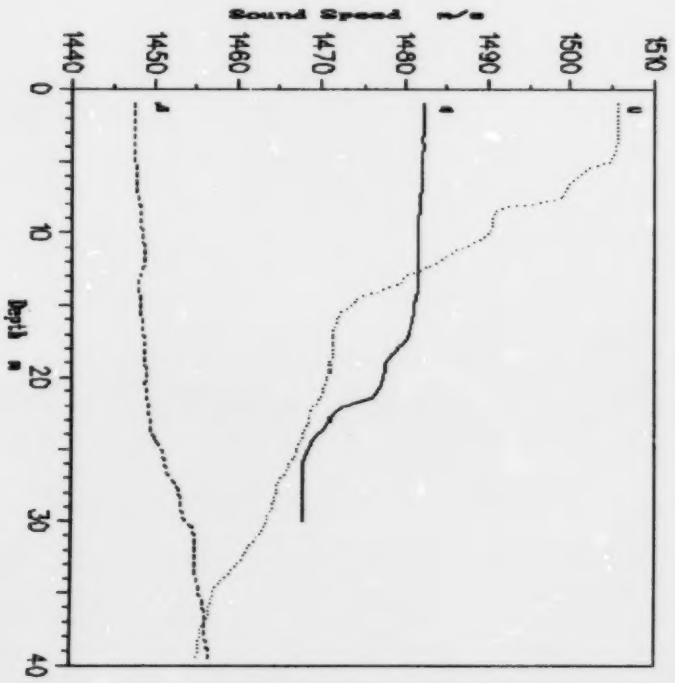


Figure 4. Sound speed profiles for the BIO data sets: a) the Hydrostar and Nautronix ATS, b) the first Trackpoint II and second Hydrostar, and c) the second Trackpoint II.

The workboat steamed on a constant heading passed the barge to create data sets in which both the bearing and range were changing simultaneously (Figure 3). These were intended to simulate typical positioning situations met operationally. These data sets will be referred to as "PASS" in the following discussion.

Figure 4 illustrates the sound speed profiles during the three trial periods. Depth-dependent conductivity and temperature were measured with a Seabird CTD then converted to sound speed according to an algorithm supplied with that instrument. The

acoustic ranges were adjusted for the sound speed which prevailed over the acoustic path during each experimental phase.

5.2. The DREP Experiment

The DREP experiments took place in Saanich Inlet, a tidal embayment on the east coast of Vancouver Island. Water depth at the site ranged from 100 to over 200 m. The hydrophone was mounted on the side of a workboat at a depth of 2.5 m. The acoustic source was suspended beneath a drifting buoy on a line

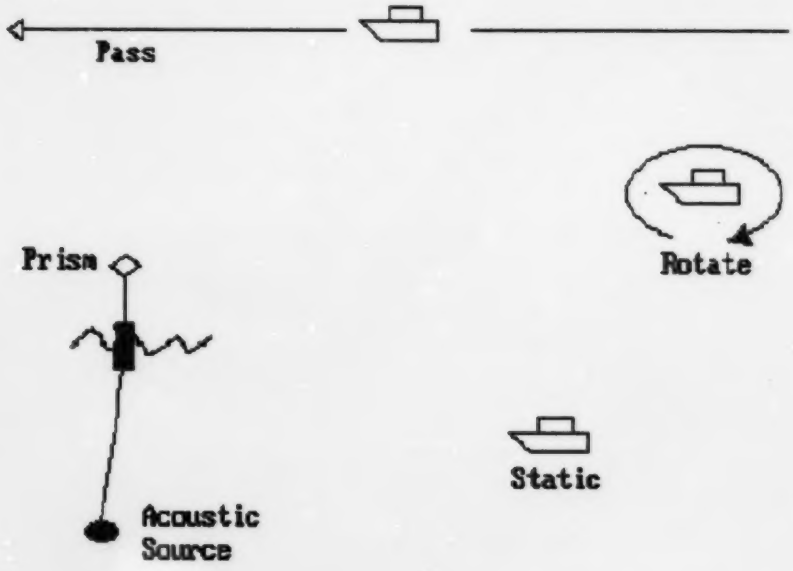


Figure 5. Geometry of DREP source/receiver for various maneuvers.

at depths of 20, 40 and 90 m. Attached to a pole on top of the buoy was a passive optical reflector. The Esprit Laser Range Finder was mounted on the workboat inboard of the hydrophone and the fixes were subsequently corrected for the resultant offset. Measurements were only carried out when winds were modest and it is known that tidal flow in the inlet is gentle. Therefore, it was assumed that any offset which might occur between the buoy and acoustic source as a consequence of wind and water current drag on the system components would be minimal.

Figure 5 illustrates the maneuvers undertaken during the course of the DREP experiments. The STATIC data sets represent

nominally constant bearing and range. The ship was not purposely being moved although at times it did drift relative to the buoy. The PASS data sets were obtained at a number of different offsets and were intended to simulate typical positioning situations where both range and bearing change simultaneously. The ROTATE data sets were obtained by using a second vessel to rotate the workboat while maintaining the range approximately constant.

6. Data Processing

6.1 Optical and Acoustic Fix Synchronization

6.1.1 Correcting Acoustic Fix Time Label

The optical and acoustic fixes occurred asynchronously and were labeled with time from a common clock as they were logged. In order to compare them, the acoustic fix time label had to be adjusted to the instant the remote acoustic source emitted its signal. This required two separate corrections to be made. First, a correction had to be made for the transit time of the signal from the remote source to the receiving hydrophone. This adjustment can be derived from the measured range and the known sound speed. Second, the interval between receipt of the acoustic signal at the hydrophone and the instant the resulting computed position is actually labeled by the logging system with the common clock time must be corrected for. This delay depends on the nature of the algorithms within the receiver, the speed of the receiver microprocessor and delays inherent in the data logging process. The delay introduced by the logging process could be determined experimentally. However, none of the manufacturers specified the receiver delays so they had to be inferred from the data sets obtained.

The Hydrostar receiver processor delay was established by matching the time of occurrence of uniquely identifiable changes in acoustic and optical bearing. Five such events were selected and, for each, the standard deviation of the bearing difference was computed for several different assumed processor delays. For each data set, there was a delay which minimized the standard deviation of the bearing error. The mean of these five optimum values, 1.6 s, was taken to be the processor timing correction. This same synchronization method was employed for both the DREP Trackpoint II and DREP Nautronix ATS data sets.

For reasons which will be described below, the only Trackpoint II data sets acceptable for analysis from the BIO experiments were one pair of RADIALs containing only bearing information. It was felt that this was insufficient to determine the receiver processing delay correction by the method used for the Hydrostar receiver. Because only bearing data was available for analysis and it was derived from source paths on approximately constant heading, no correction was made for receiver processor delay.

The BIO data sets for the Nautronix ATS receiver were used to examine its processor delay in somewhat more detail. The Nautronix ATS receiver attaches a time label derived from an internal clock to the fix as soon as the signal arrives at the hydrophone. This clock is different from the one used in common to label the optical and acoustic fixes. The difference between the two time labels was examined for a long series of fixes at ranges from 86 to 1196 m. It was found to be constant to within the resolution of the clocks (1.0 s for the ATS Receiver and 10 ms for the data logger) which indicates that there was no

detectable variation in the time required by the receiver to process individual fixes.

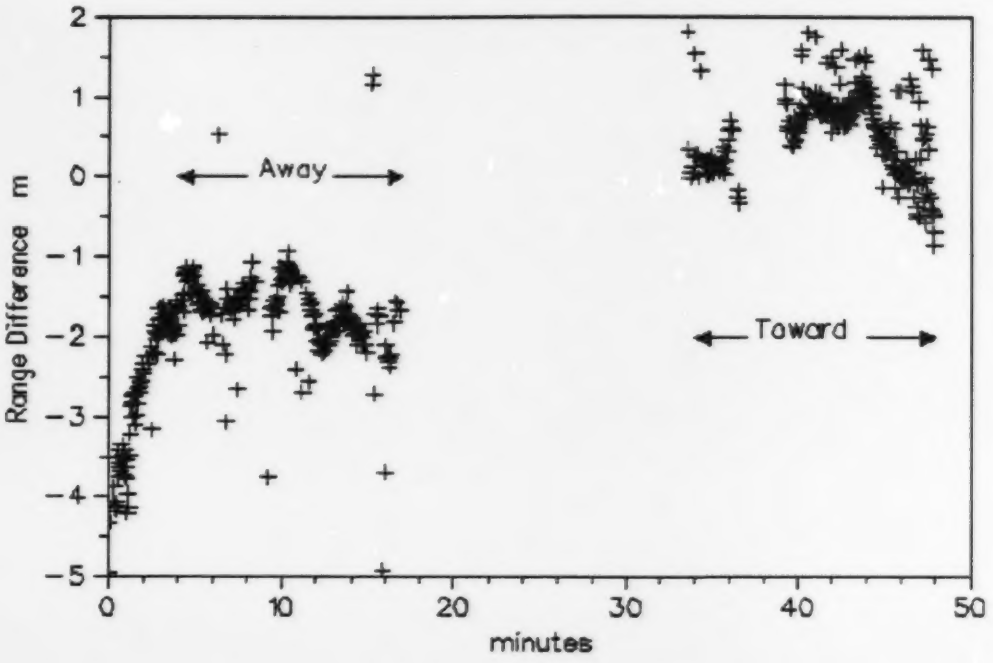


Figure 6. Nautronix ATS range error time series before correcting for the receiver processor delay.

The next problem addressed was the establishment of the magnitude of this apparently constant processor time delay. A reciprocal pair of RADIAL data sets was selected and the time labels of the acoustic range data were corrected for the travel time between the source and hydrophone but not the unknown processor delay. Figure 6 is a time series plot of the apparent acoustic range error. It is clear that there is a systematic offset between the "away" and "toward" radials. This offset is caused by the processor delay in the receiver. Various constant processor delays were then applied to the aforementioned data sets and the mean range difference of the "away" and "toward" data sets were computed. The relationship between this difference and the assumed processor delay was found to be a linear one. A receiver processor delay correction of 1.85 s caused the difference between these means to be reduced to zero. It is important to note that this correction may also contain certain other constant delays introduced by the nature of the experimental setup.

6.1.2 Optical Position Coincident with the Acoustic Fix

The PolarFix and Esprit optical systems neither produce a fix in

response to an external trigger nor provide a trigger pulse which could be used to initiate an acoustic fix. Therefore, the instant they fix the position of the remote source is independent of the time any particular acoustic position is established. However, in order to compare the two systems, the optical position at the instant the acoustic source emits its signal is required.

During the first part of the BIO experiments, PolarFix positions were obtained every 2.5 s. During the latter part, the update rate was increased to three per second. For all of the data analyzed, the PolarFix range and bearing were noise free and smoothly varying functions of time as illustrated in Figure 7.

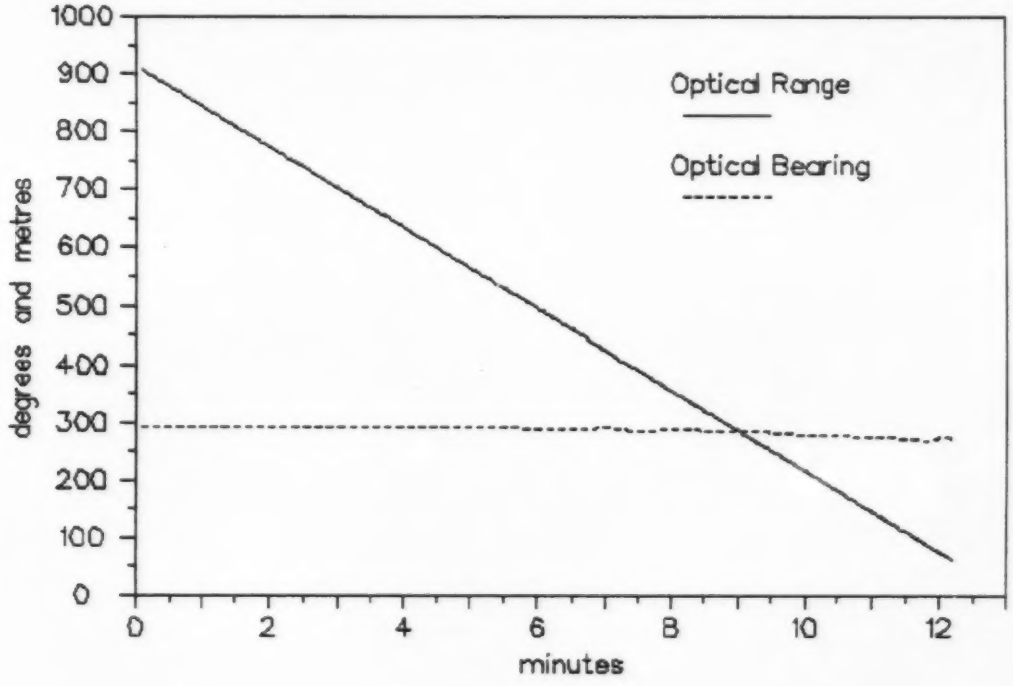


Figure 7. Typical Atlas PolarFix time series during a RADIAL.

In order to compute the range and bearing errors of the acoustic fix, the optical equivalents are required at the same instant. These were established by fitting separate second order polynomial curves to PolarFix range and bearing time series 20 s either side of the acoustic fix of interest. The Polar Fix system appends a quality metric of 0 to 9 to the range/bearing pair. The method of its computation is unknown. It was arbitrarily decided that only fixes with a quality exceeding 5 would be utilized to create the fitted curves. The optical range and bearing at the instant of the acoustic fix were then computed from these fitted curves.

In the case of the DREP experiment, optical fix data were collected three times per second. The optical position corresponding to the instant of the time of acoustic fix was obtained by averaging the two sets of optical range/bearings which bracketed it.

6.2 Hydrophone Offset Corrections

6.2.1 The BIO Experiment

It was intended that there be no geometric offsets between the acoustic hydrophone and the PolarFix optical transceiver nor the acoustic source and the optical prism. For this reason, the laser transceiver was located vertically above the acoustic hydrophone and the optical reflector and acoustic source were mounted on either end of a rigid vertical pole.

During subsequent analysis of the Nautronix ATS data set, a systematic range-dependent error was identified in both range and bearing data. The onset of this error coincided with an entry in the field notes to the effect that the ATS receiver operators were applying geometrical offsets to the real-time graphic display at that time. Apparently, unlike the Hydrostar and Trackpoint II, the positions this receiver supplies to the logging port incorporate any offsets that might be introduced by the operator. Furthermore, there is no indication in the logged data set as to the presence or magnitude of these offsets. It was assumed that the systematic error observed was caused solely by the presence of incorrect hydrophone offsets in the logged data. Its magnitude was inferred and the data corrected accordingly.

6.2.2 The DREP Experiment

The geometric offset between the location of the acoustic hydrophone and the Esprit optical transceiver aboard the workboat was measured and all data adjusted to correct for it. The acoustic source was suspended on a weighted line at various depths below a float which in turn supported a pole to which the optical prism was attached. Wind drag on the buoy and tidal current drag on the underwater line inevitably caused some uncertainty in the horizontal position of the transponder relative to the optical prism. This matter will be discussed further in sections 8.2 and 9.3.

6.3 Statistical Analysis of Range and Bearing Errors

The DREP optical and acoustic fixes were merged, then manually edited to remove fixes which appeared to contain anomalously large errors.

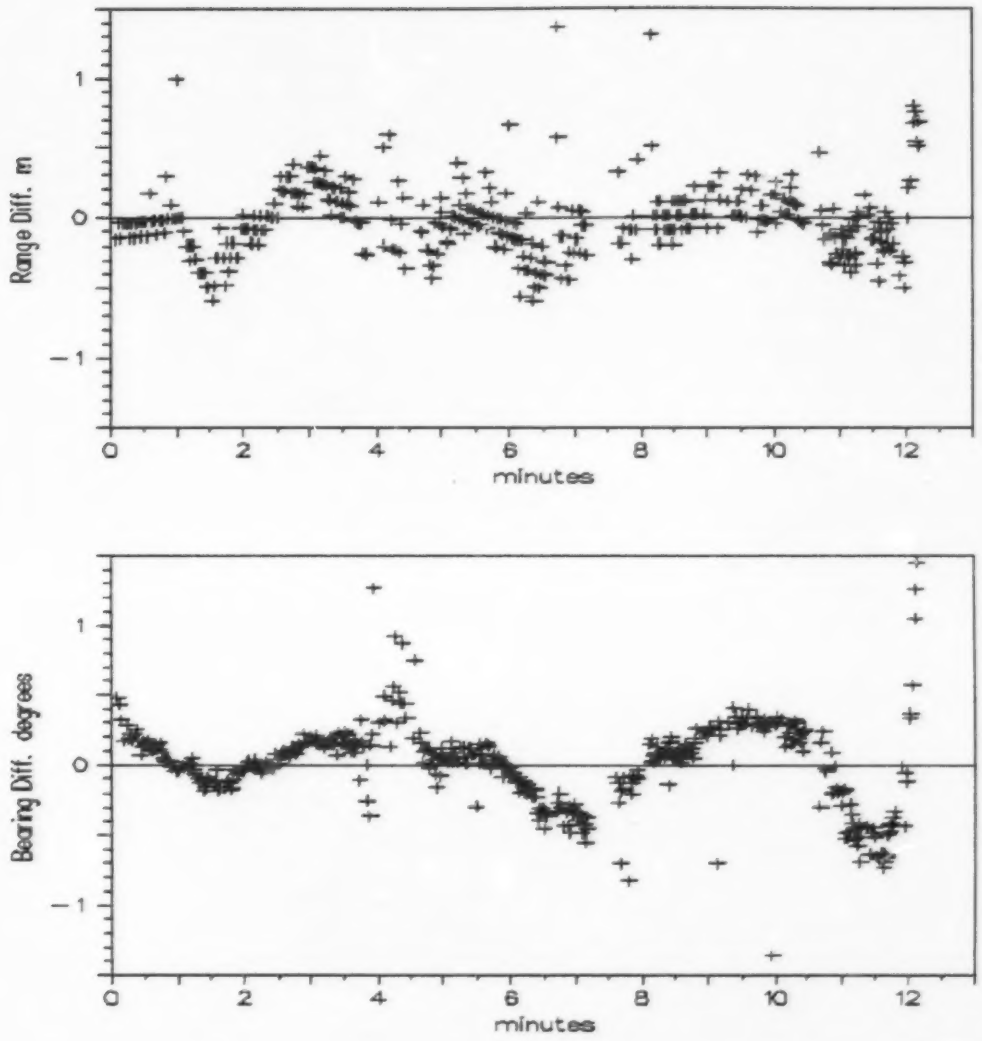
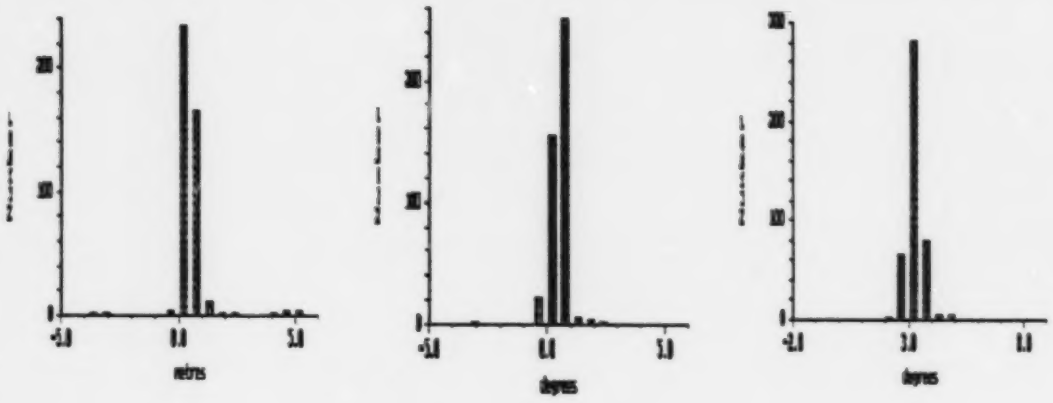


Figure 8. Range and bearing error time series for RADIAL #2, Nautronix ATS receiver.

No editing or filtering of the BIO data was done other than that inherent in the curve fitting method employed to derive the optical position at a time coincident with that of the acoustic fix. The mean and standard deviation of each RADIAL, PASS, etc. were then computed after applying +/-5 m and +/-5^{o} windows to the range and bearing errors respectively. Figure 8 illustrates these error time series for Nautronix ATS RADIAL #2, the one which corresponds to the optical range and bearing data of Figure 7. Figure 9 shows the corresponding error histograms. The term "corrected bearing difference" will be explained later. The errors are Gaussian in nature so that they can be conveniently

quantified by computing their means and standard deviations.



A) B) C)

Figure 9. Histograms of the A) range, B) bearing and C) corrected bearing errors for RADIAL #2, Nautronix ATS receiver.

7. Hydrostar

7.1 Range and Bearing Time Series

The Hydrostar receiver employed in these trials was an early model which lacked an ability to measure the range to an acoustic transponder. While it purports to measure range to a free running pinger, it has been demonstrated that the data is of little practical value (McKeown, 1990).

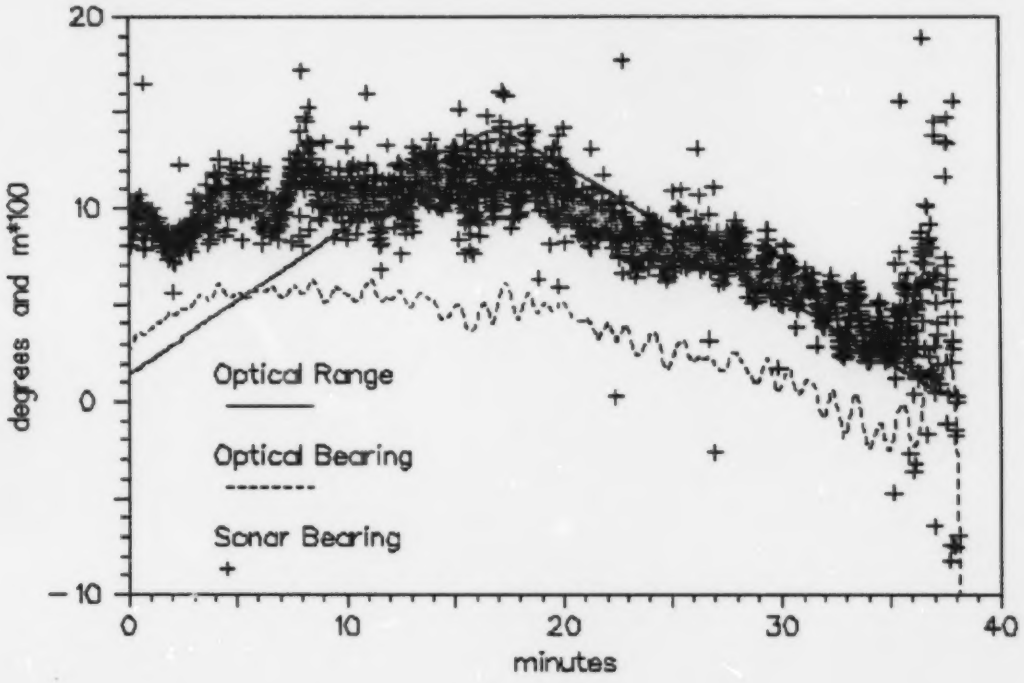


Figure 10. Hydrostar relative bearing and corresponding optical range and bearing time series for RADIALs #5 and #6.

Figure 10 is an example of the measured, unedited bearing time series for RADIALS #5 and #6. The high frequency oscillations evident in the optical bearing time series are caused by the barge swinging back and forth on its four-point mooring under the influence of the wind. The same oscillations are present in the acoustic bearing data but are somewhat masked by the bearing "noise". Their presence has no affect on the intercomparison because they are common to both systems and are eliminated when bearing differences are computed.

There were occasionally single measurements of acoustic bearing which were both anomalous with respect to the adjacent ones and with respect to the corresponding optical measurement (spikes). During these trials, there were no periods when major bearing errors persisted for any length of time. Nevertheless, during

the course of other experiments, it has been observed that the indicated bearing will on occasion suddenly change by a multiple of 120° for a number of fixes then switch back again to values much closer to the correct value.

7.2 Systematic Range and Bearing Errors

Two ARC data sets were collected. A strong correlation between bearing error and the bearing of the measurement was noted (Figure 11). This bearing-dependent error had a sinusoidal form

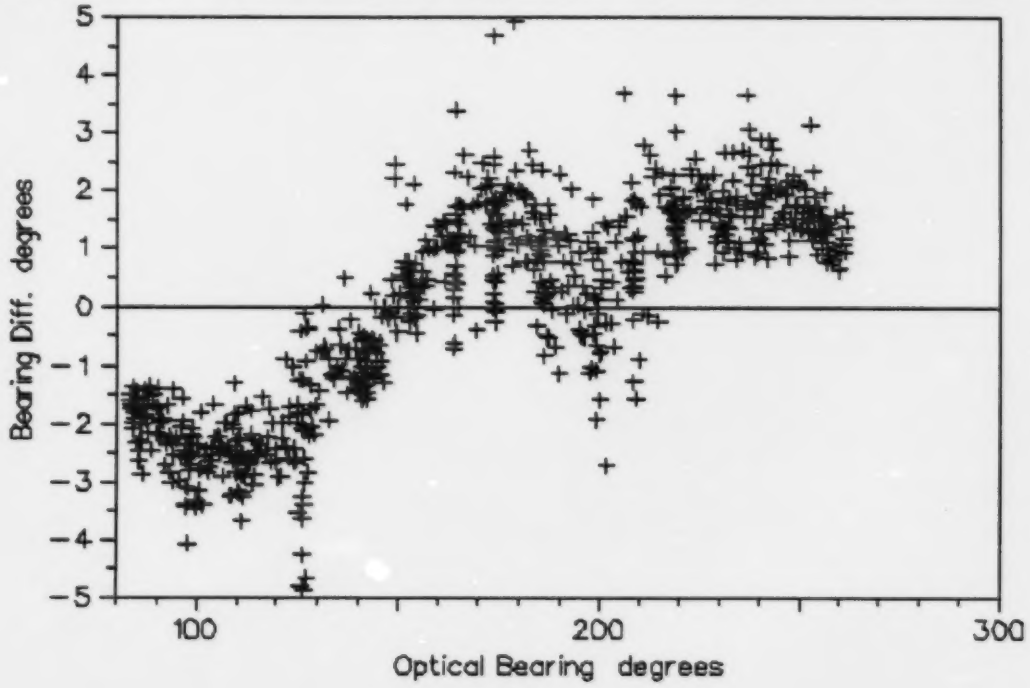


Figure 11. Hydrostar bearing error illustrating its sinusoidal dependence on the actual bearing.

very analogous to the deviation error curve exhibited by a magnetic compass so it was designated the acoustic deviation error. The following function was fitted to the error curves:

$$\text{Acoustic Deviation Error} = \text{Offset} + A * \sin(B + C)$$

where

Offset = difference between acoustic and optical reference directions
A = peak amplitude of the sinusoidal correction
B = actual measured acoustic bearing
C = angular offset between the reference direction of the acoustic system and point where the deviation correction is zero

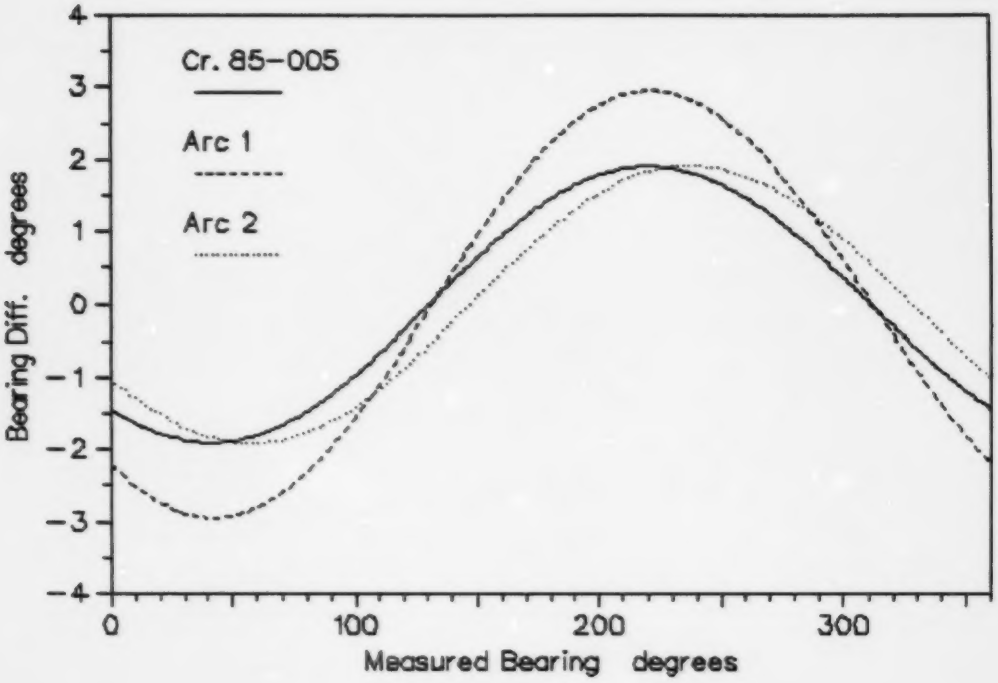


Figure 12. Acoustic deviation curves fitted to three different Hydrostar data sets.

Figure 12 shows the fitted curves for ARC #1 and #2 and also a deviation curve for the same receiver and hydrophone that was obtained some years ago (Cr. 85-005) during a similar calibration procedure in a different installation. The calibration is very repeatable and undoubtedly represents residual geometric and electronic bearing errors within the receiver that are not removed by the factory calibration procedure. Application of this deviation correction to the ARC data set reduced the standard deviation of the bearing error of ARC #1 by 48% and ARC #2 by 31%. There was no detectable range-dependent bearing error evident in any of the RADIAL data sets.

7.3 Hydrostar Bearing Error Statistics

Figure 13 illustrates representative bearing error histograms for each of the four basic types of data sets, RADIAL, PASS, ARC and STATIC. The typical bearing error tends to be symmetrically distributed about some mean value and almost all the errors fall within a $+/-5^{\circ}$ window. Bearing error means and standard deviations were derived by computing a mean, setting an acceptability window of $+/-5^{\circ}$ about it to eliminate outliers, then recomputing the mean and finally the standard deviation.

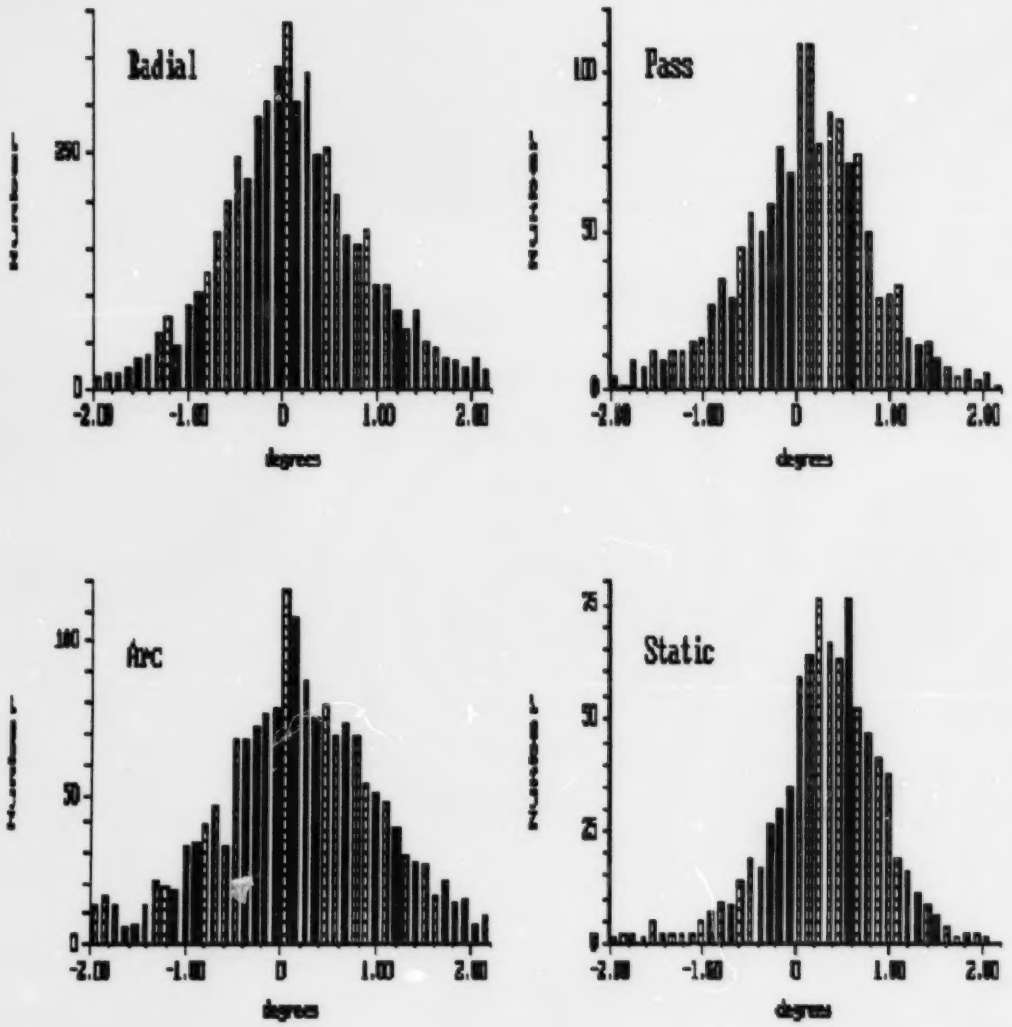


Figure 13. Hydrostar bearing error histograms for typical RADIAL, PASS, ARC and STATIC data sets.

Table 1 summarizes the statistics for all the Hydrostar data sets. The RADIAL and STATIC maneuvers occur at approximately constant relative bearing so that the correction for the systematic bearing-dependent bearing error as discussed in section 7.2 only affects the ARC and PASS data. The effect of the correction on the PASS data is not very apparent because, over much of the track, the bearing is in fact only changing slowly. No position errors can be computed for this receiver because, in the configuration tested, it does not measure range.

Table 1. Hydrostar Relative Bearing (RB) Error Statistics

Data Set	dZ (m)	Num Fix	Range (m) Min.	Range (m) Max.	RB Span	RB Diff. Std. Unc	RB Diff. Dev. Cor
RADIAL							
#1	0	1045	55	1556	34.6°	0.74°	0.79°
#2	0	1256	61	1689	9.9	0.69	0.75
#3	0	621	89	1243	6.2	0.80	0.77
#4	0	763	309	1232	6.2	0.72	0.67
#5	0	842	162	1385	3.1	1.32	1.31
#6	0	984	134	1389	8.6	0.97	0.94
ARC							
#1	0	737	329	369	173.5	1.73	0.89
#2	0	785	310	332	185.2	1.58	1.10
STATIC	0	916	171	180	6.8	1.03	1.00
PASS							
#1	0	353	192	350	95.6	1.54	1.49
#2	0	272	227	336	85.3	1.53	1.56
#3	0	351	195	312	94.1	0.65	0.64
#4	0	256	216	326	96.2	0.57	0.58
#5	0	325	198	313	100.2	0.92	0.89

8. Trackpoint II

8.1 Range and Bearing Time Series

One pair of reciprocal RADIALs was run using a Hydrostar pinger as an expedient substitute for an inoperative Trackpoint II transponder. Figure 14 is an example of the measured, unedited bearing time series for RADIALs #1 and #2. The high frequency oscillations evident in the optical bearing time series are believed to be caused by the barge swinging back and forth on its four-point mooring under the influence of the wind. The same oscillations are present on the acoustic bearing data but are somewhat masked by the bearing "noise".

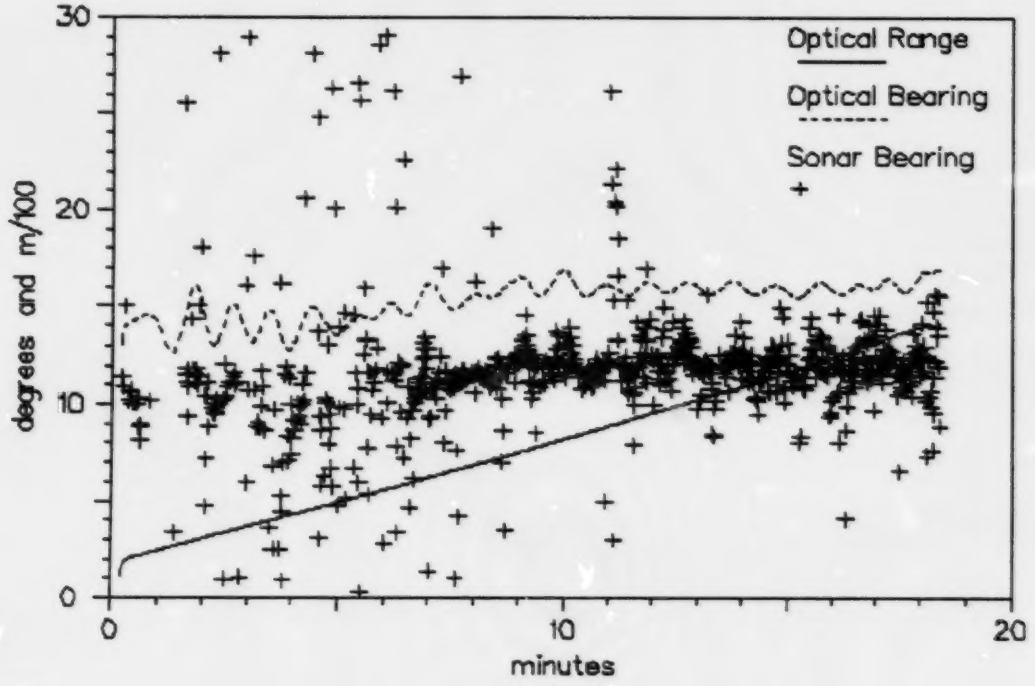


Figure 14. Trackpoint II relative bearing and corresponding optical range and bearing time series for RADIALs #1 and #2.

During both the DREP and BIO experiments, there were no occasions when the Trackpoint II bearings deviated from the optical ones by a significant amount for any period although there were occasional spikes or singular bad readings. However, during the BIO experiments with the pinger source, the acoustic bearing data showed considerable variability at ranges of less than 400 m. Possibly shallow water reverberation and the use of a pinger instead of a transponder was the source of the problem. If so, the problem might have been solved by adjusting the receiver gain and threshold levels but time constraints did not permit

experimentation. A +/-5^{o} bearing error window applied to these data sets during the analysis process minimizes the influence this has on the overall statistics.

Some seven months later, in August 1990, another opportunity arose to evaluate the Trackpoint II at BIO. Operational constraints dictated that the geometry of the experiment had to be reversed, that is, the hydrophone and PolarFix were mounted on a ship and the transponder plus prism were secured to the side of the barge. It was accepted that the resultant acoustic noise field near the hydrophone would be substantially higher than during the trials of the other two receivers making a true intercomparison difficult. Two variants of the Trackpoint II receiver software were tested. The first was the DREP receiver in its original "as delivered" state with version 5 software. The second was the same receiver temporarily upgraded to version 7 software.

When the RADIAL data was analyzed it was found that the range errors clustered about several significantly different mean values (Figure 15). Both the original and the upgraded receivers exhibited this effect although the latter to a much lesser extent.

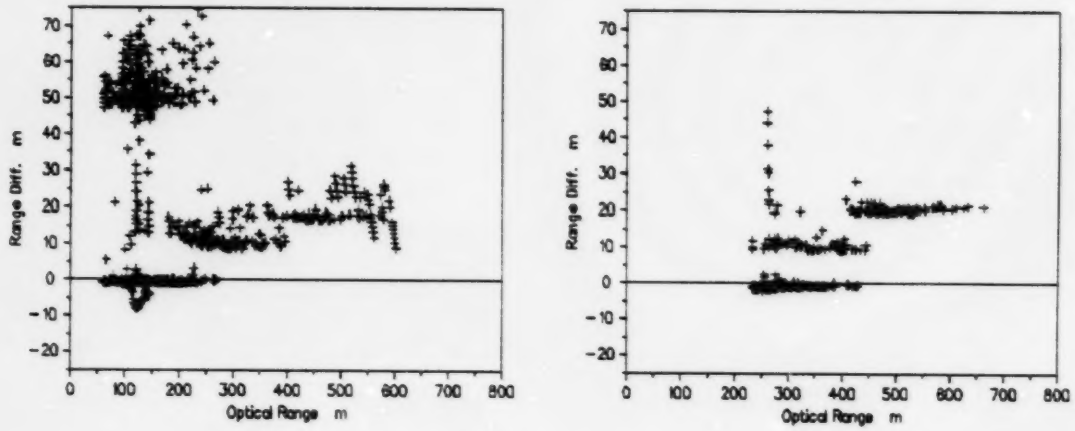


Figure 15. Scatter plots of range error for a) the original DREP receiver and b) the same receiver upgraded to the latest standard.

Examination of the sound speed profile prevailing at the time (Figure 4) suggested that the clusters at mid and long range might well be caused by refraction problems. Simple ray plots indicated that the limiting range for a direct ray might be in the order of 200 to 300 m. Other acoustic work in the same basin during the previous fortnight had demonstrated ray bending causing limiting ranges of this order (Trenholm, 1990). Figure 16 is an example of a sub-set of the range error data of Figure

15 along with an error model created by assuming the received signal arrives via a bottom reflection but is assumed to have traveled by a direct path. All of this is highly suggestive that the data sets are badly contaminated by refraction effects.

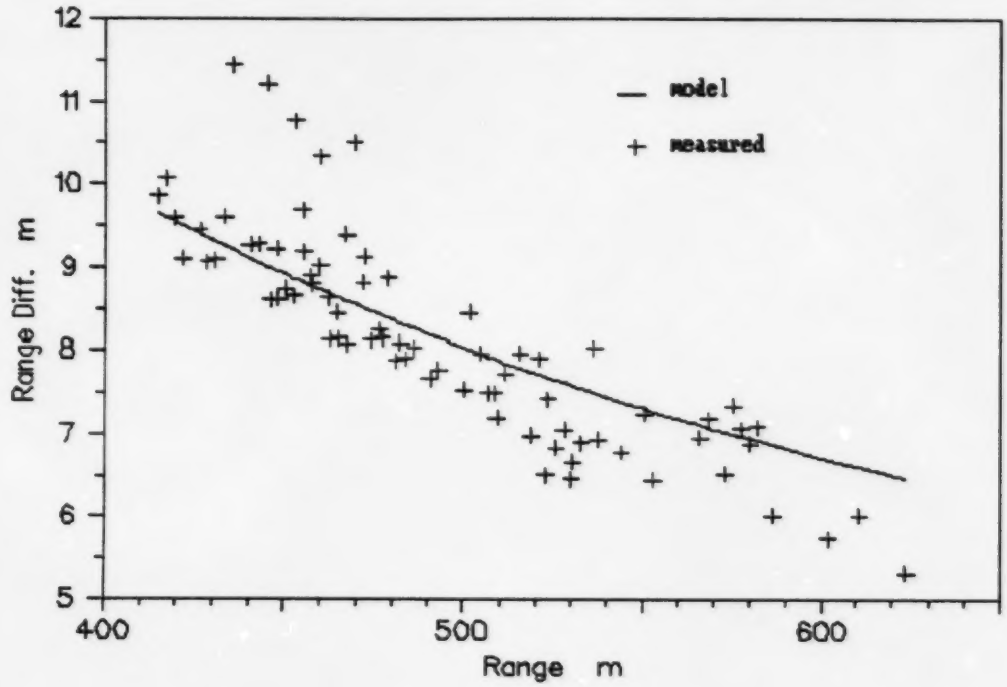


Figure 16. Measured acoustic range errors over ranges of 400 to 500 m and those based on a model which assumes the source/receiver path is via a bottom reflection.

The range and bearing error data sets for the August 1990 RADIAL, ARC and STATIC maneuvers were analyzed as described in section 6.0. Error statistics were computed only for fixes where the range error was less than +/-5 m on the assumption that these fixes resulted from a direct source/receiver acoustic path. As Table 2 indicates, the standard deviations of the relative bearing error for the various August 1990 data sets were much higher than those of the earlier trial. It is thought that this is a consequence both of the acoustic propagation problem outlined above and the location of the hydrophone on a noisy, moving ship. It is believed that the August 1990 Trackpoint II data sets are not comparable to those for the other receivers. Therefore, they have been excluded from further consideration.

Table 2. Trackpoint II Bearing Errors

Data Set	Source	Receiver Config.	Number of Fixes	Std. Dev.
Jan.	Pinger	Original	1494	1.175°
Aug.	Xpndr	Original	1365	1.850
Aug.	Xpndr	Upgraded	1298	1.818

8.2 Systematic Range and Bearing Errors

The DREP data sets all showed systematic range and bearing errors. While the form varied somewhat between data sets, the error time series depicted in Figure 17 was typical. The optical prism was mounted on a surface buoy and the acoustic source was suspended beneath it on a weighted wire. It is possible that wind drag on the buoy in conjunction with tidal current drag on the wire generated a horizontal displacement between the two. To test this hypothesis, a model was created which described the optical/acoustic range and bearing errors as a function of distance along the ship's track as it passed the buoy. Two models were created: one in which the offset of the acoustic source with respect to the prism both parallel and orthogonal to the ship's track remained constant, the non-time variant model; and one in which the optical prism/acoustic source offset was allowed to vary as the ship passed the buoy, the time variant model.

Figure 17 illustrates the measured range and bearing errors as a function of the distance along the ship's track (time) for the acoustic receiver/transponder geometry of PASS #5. These polar time series were converted to orthogonal components in a rectangular coordinate system with one axis lying along the ship's track. The resulting error components were nearly constant but also showed a simple, near linear time dependency. Their mean values, 2.1 m along and 3.3 m across the ship's track, were assumed to represent the offset of the acoustic source with respect to the prism and were entered as such in the non-time variant model described above. A linear function was fitted to each rectangular error component to describe the time varying offset in the time-variant model. The resultant modeled range and bearing errors are superimposed on the measured data of Figure 17 for PASS #5 for both cases. The close agreement in form between the models and the observed errors suggests that there may be some validity to the hypothesis that the time-varying errors are caused by an offset between the prism and the acoustic source. If the non-time variant model is used to adjust the data of PASS #5 for this postulated offset, the standard deviation of the range error is reduced from 2.55 to 1.35 and that of the bearing error from 1.83° to 1.51°. Adjustment via the time variant model further reduced the range error to 0.85 m and the bearing error to 1.25°.

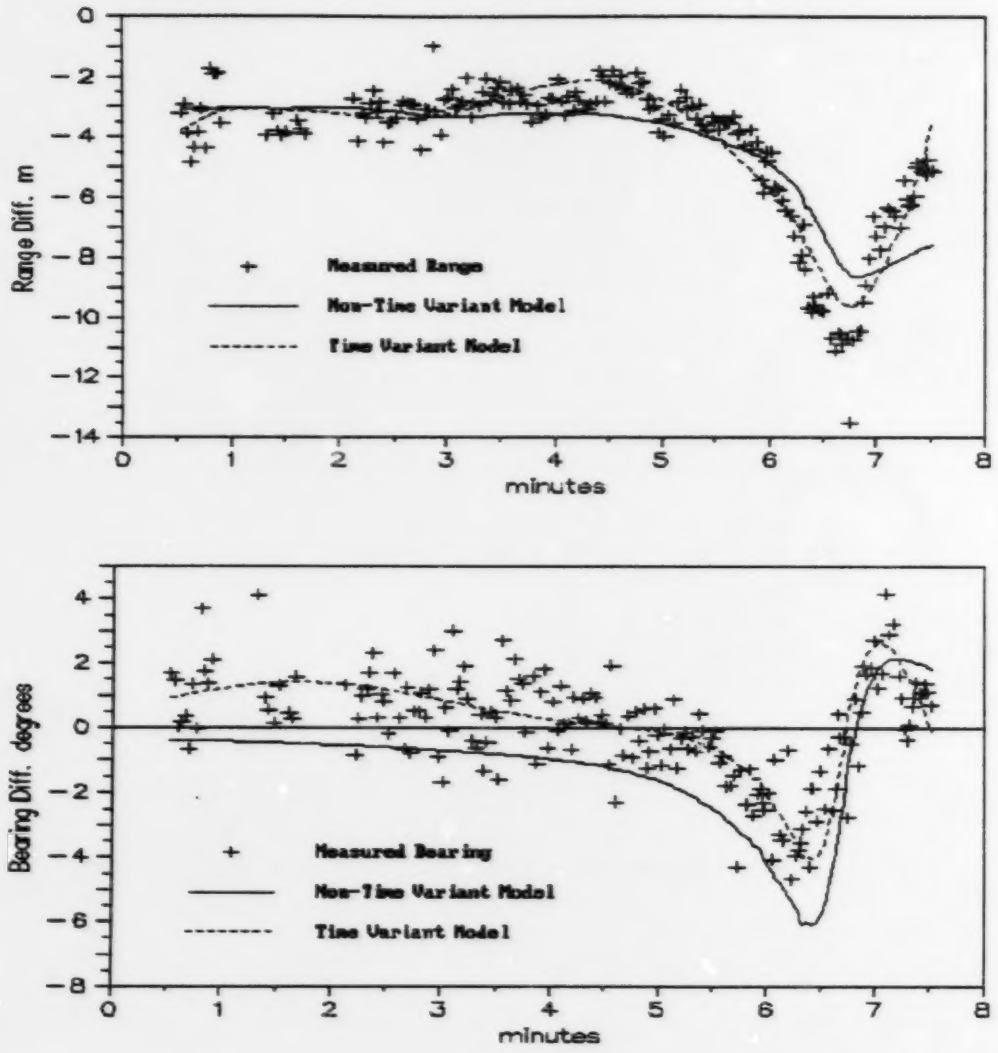


Figure 17. Measured and modeled range and bearing errors for PASS #5.

The effects of other possible error sources such as:
1. Incorrect remote source depth;
2. Incorrect sound speed;
3. Movement of vessel during fix;
4. Incorrect synchronization of acoustic and optical fixes;

were incorporated into the same model. When the prism/acoustic source offset was set to zero and each of these potential error sources was implemented separately and in various combinations, none correctly represented the observed error time series.

When the same error model was applied to several other DREP data sets, the degree of correction was noticeably poorer. The construction of unique models with time varying offset for each of the data sets would be a time consuming activity. Furthermore, there is the possibility that the application of such a scheme to correct systematic experimental errors would mask real peculiarities in receiver performance. Therefore, no further attempt was made to correct the observed errors for systematic error sources.

8.3 Trackpoint II Bearing Error Statistics

Because there was no acceptable ARC or ROTATE data, no deviation curve analogous to that for the Hydrostar receiver could be derived. Consequently, no corrected relative bearing errors could be computed. The same +/-5^{o} bearing error window as was used for the Hydrostar data sets was applied in this case. Table 3 summarizes the results for the data sets ultimately deemed acceptable.

Table 3. Trackpoint II Range and Bearing Error Statistics

Data Set	dZ (m)	Num Fix	Range (m) Min.	Range (m) Max.	RB Span	Rng Diff Std Dev (m)	RB Diff Std Dev
RADIAL							
#1	0	777	210	1408	4.5^{o}	-	0.98^{o}
#2	0	815	171	1408	9.8	-	1.53
STATIC							
#1	20	190	35	45	20.6	0.41	0.49
#2	40	70	75	96	25.6	0.38	0.53
#3	90	220	62	86	13.6	0.37	0.42
ROTATE							
#1	20	230	174	220	353.9	1.93	2.51
#2	40	260	34	92	392.2	1.85	2.55
#3	90	340	82	143	341.7	2.09	2.27
PASS							
#1	20	140	22	396	161.1	1.69	1.77
#2	20	280	18	412	187.2	1.64	1.89
#3	20	190	50	442	164.1	1.28	1.43
#4	40	260	61	486	179.2	1.31	1.59
#5	40	350	28	527	182.8	1.40	1.64
#6	90	510	24	909	183.6	2.44	1.85
#7	90	210	34	312	190.6	1.55	1.88

As was pointed out in section 8.2, the DREP data contains a systematic geometric error of a magnitude similar to the positioning errors being quantified. It was postulated there that they result from the experimental method rather than

receiver performance. The impact of this geometric error on the range and bearing errors is minimized in the STATIC data sets where both the range and bearing remain relatively constant. There it tends to appear as a constant contribution to the error of each individual fix and can be eliminated through an averaging process. If this is done then the errors derived from the DREP and BIO STATIC maneuvers can be meaningfully compared. On the other hand, the DREP PASS and ROTATE data sets do contain significant systematic geometric errors which cannot be eliminated. Table 3 includes the data sets that exhibit this systematic error. However, the variable effect of the source/prism offset on the range and bearing errors for each maneuver must be remembered when studying the results depicted.

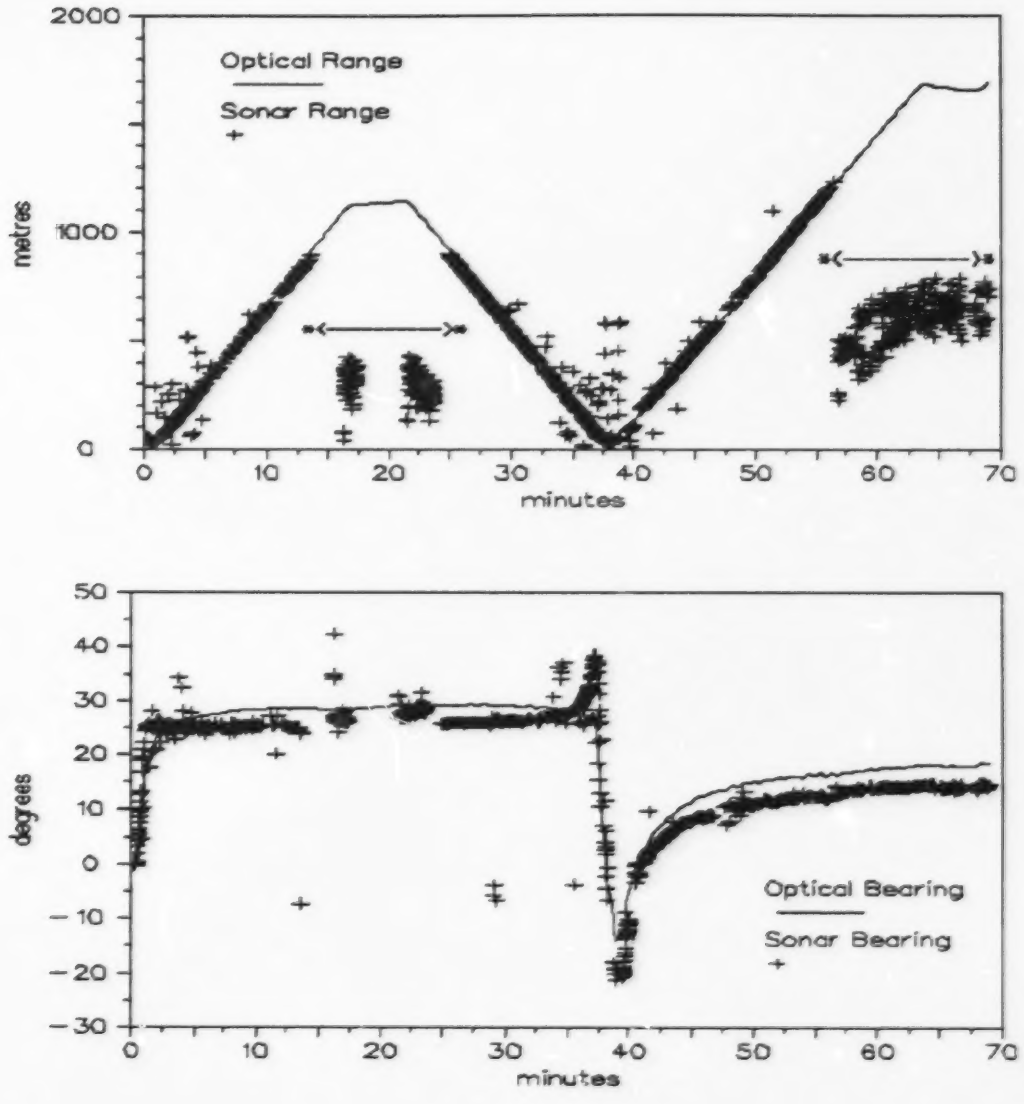


Figure 18. Time series of Nautronix ATS and PolarFix range and bearing showing anomalous behavior of the range measurements at segments marked *<----->* .

9. Nautronix ATS

9.1 Range and Bearing Time Series

In addition to singular anomalous measurements or spikes from time to time, both the Nautronix range and bearing time series exhibited some unusual behavior. Figure 18, the data for RADIALs #1, #2 and #3, illustrate two periods where the measured range suddenly changes by a substantial amount Although the indicated bearing remained well behaved, there were examples of sudden dramatic bearing changes such as those evident in PASS #3, Figure 19.

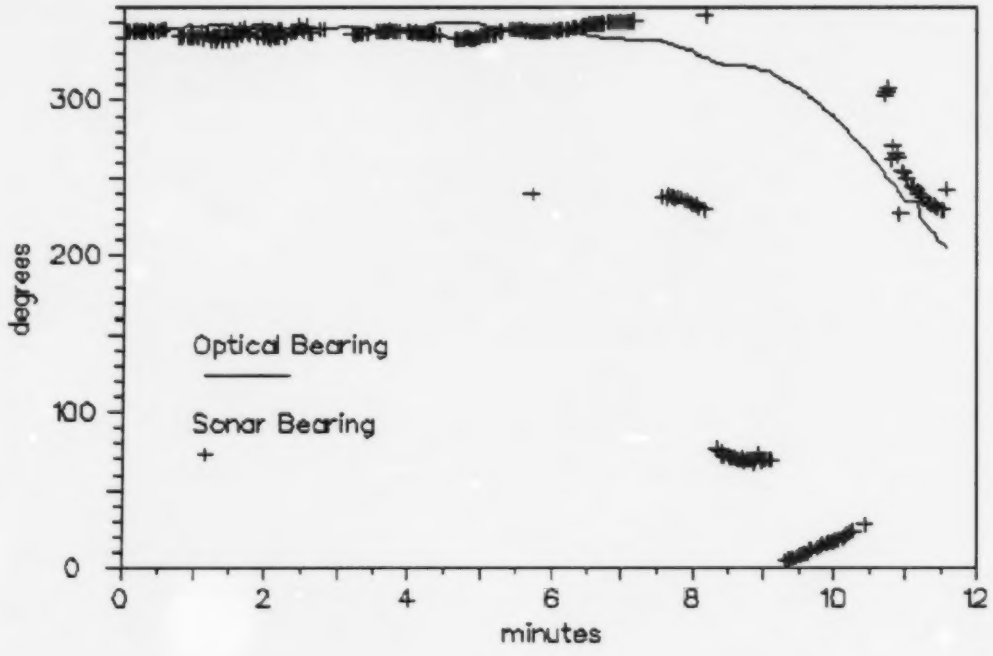


Figure 19. Nautronix ATS and PolarFix relative bearing time series during PASS #3 showing various periods when the former suddenly changed by a significant amount.

9.2 Systematic Range and Bearing Errors

There was no evidence in any of the BIO or DREP data sets of any systematic range-dependent range or bearing errors. However, both the ARC and ROTATE data, that is, nominally constant range and steadily varying bearing, indicated that the bearing error was a strong function of acoustic bearing. This effect appears to be similar to that noted for the Hydrostar receiver (section 7.2). As was done in that case, sinusoidal curves were fitted to the data. As can be seen in Figure 20, the curves derived in

this manner for each of four different data sets yield very similar results. Figure 21 illustrates the improvement that is achieved in bearing measurement when this correction is applied to the ARC data set. The corrected time series has been offset by -2^{o} in order to make it more visible. Application of this correction reduced the standard deviation of the bearing error for the ARC data from 0.71^{o} to 0.36^{o}.

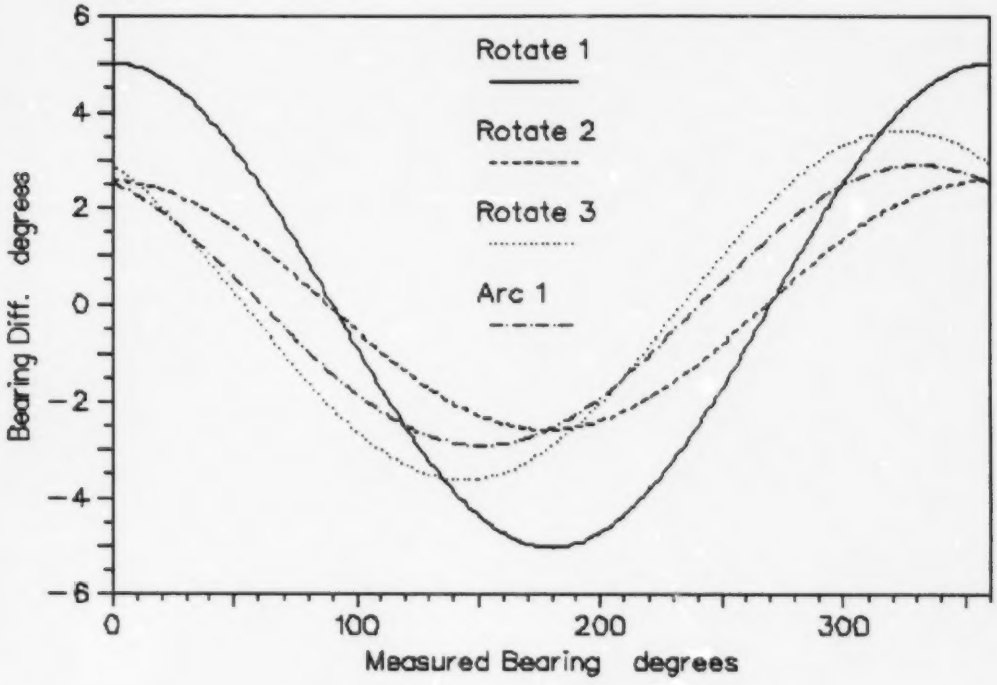


Figure 20. Acoustic bearing deviation curves derived by separately fitting sinusoidal functions to ARC and ROTATE #1, #2 and #3 data sets.

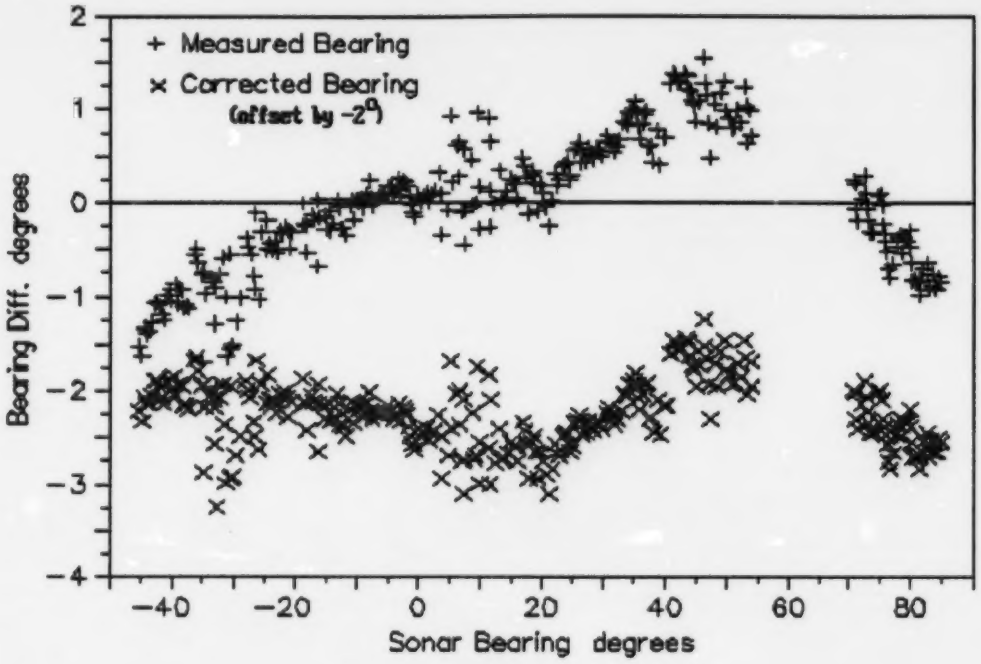


Figure 21. Nautronix ATS relative bearing error time series for the ARC data set before and after correction for the acoustic deviation error.

9.3 Nautronix ATS Range and Bearing Error Statistics

To maintain consistency with the analysis of the Hydrostar and Trackpoint II data sets, a +/-5° window was applied to the bearing errors before statistics were computed. In addition, a +/-5 m range error window was applied in order to remove the effects of errors such as those illustrated in Figure 19.

Large systematic errors were observed in the range and bearing error time series for the DREP data sets. These appear to be similar to those noted in the DREP Trackpoint II data sets as described in section 8.2. Figure 22 illustrates the range and bearing errors both for the actual measured data and those which would theoretically occur if the acoustic source were offset 5.6 m with respect to the optical prism. The effect of wind on the buoy supporting the prism and tidal current drag on the wire supporting the acoustic source beneath it could easily generate such a displacement.

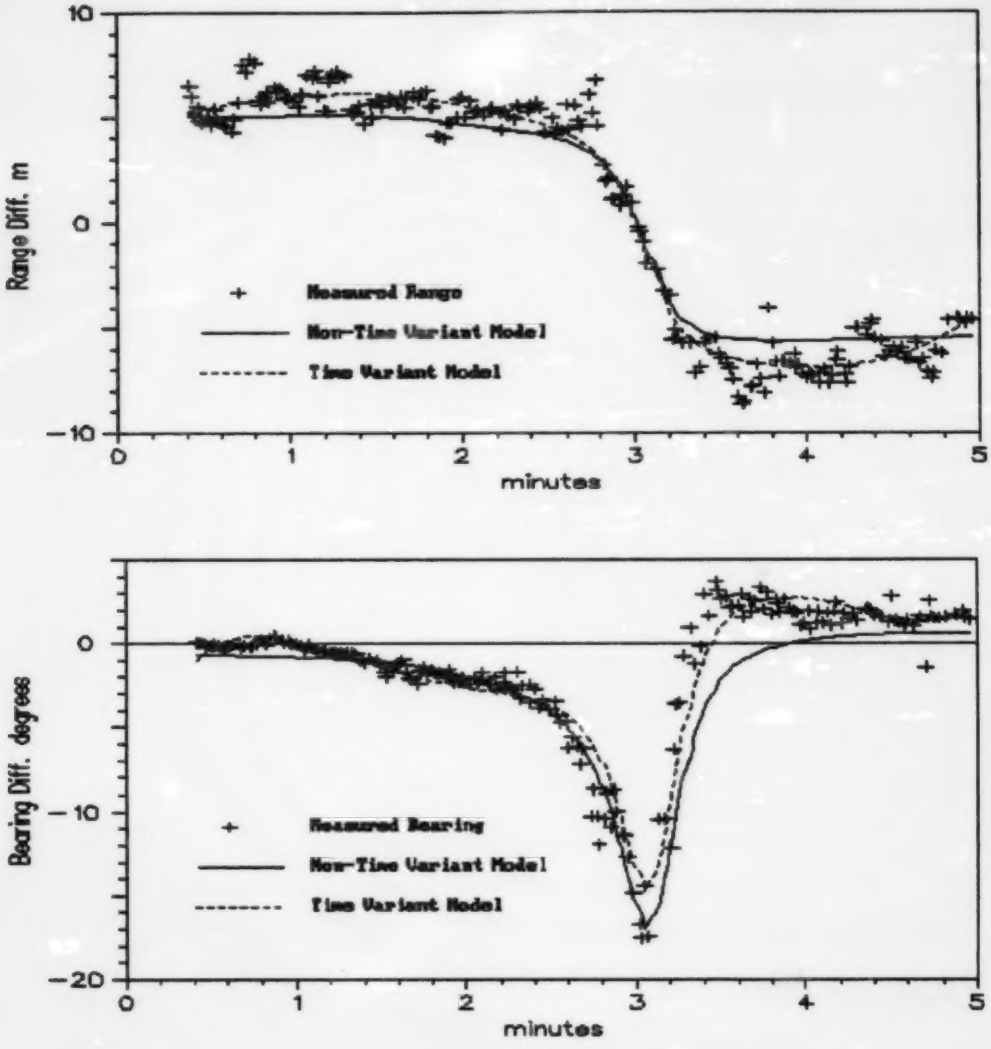


Figure 22. Measured and modeled range and bearing errors for PASS #5.

All of the DREP Nautronix data sets exhibited systematic range and bearing errors similar to those described above for PASS #5. It is presumed that the source of this error was a horizontal offset between the optical and sonar systems at the buoy. For each data set, a non-time varying offset was assumed and used to adjust the measured sonar range and bearing. In all cases, the magnitude of the postulated offset required to remove the systematic error amounted to only a few metres. The statistics for the range and bearing errors resulting from this adjustment process are listed in the "Adj" columns along with the original unadjusted values in the "Org" columns of Table 4.

Table 4. Nautronix ATS Range and Relative Bearing (RB) Error Statistics

Data Set	dZ (m)	Num Fix	Range (m) Min.	Range (m) Max.	RB Span	Range Diff Std. Dev. (m) Org	Range Diff Std. Dev. (m) Adj	RB Diff. Std. Dev. Org	RB Diff. Std. Dev. Adj
RADIAL									
#1	0	352	65	906	11.6°	0.91	-	0.59°	0.58°
#2	0	457	63	906	2.5	0.62	-	0.45	0.45
#3	0	718	167	1216	23.0	1.17	-	0.39	0.34
#4	0	593	113	888	19.2	0.63	-	0.35	0.24
#5	0	364	152	1196	12.0	0.85	-	0.72	0.38
#6	0	282	87	893	30.1	0.55	-	0.21	0.21
ARC	0	287	285	310	129.4	0.42	-	0.71	0.36
STATIC									
DREP	40	249	78	81	22.3	0.26	0.27	0.40	0.28
BIO	0	358	211	224	8.0	0.29	-	0.43	0.36
ROTATE									
#1	40	495	50	175	207.5	1.14	1.52	1.75	0.89
#2	90	449	150	177	366.8	1.85	1.81	1.91	1.03
#3	20	360	180	368	298.2	1.75	2.20	2.09	1.73
PASS									
#1A	40	161	30	363	68.2	1.56	1.95	1.38	1.31
#1B	40	276	33	371	167.0	2.57	1.83	1.83	1.11
#1C	40	43	94	170	1.3	0.78	0.79	0.37	0.43
#3	90	249	240	810	11.3	0.92	0.94	1.05	0.98
#4	90	99	33	173	22.0	0.80	0.94	1.27	1.85
#5	20	385	19	338	174.0	3.42	1.06	1.53	0.98

Note: dZ is the difference between hydrophone and transponder depths.

9.4 Position Accuracy

As indicated in section 3, the position error of an acoustic range/bearing receiver is a combination of the effects of the radial or range error and the tangential or bearing error. To quantify the resultant position error, the concept of the CEP66 radius circle which encompasses 66% of the fixes can be employed (section 3). Its definition is applicable only when the range remains relatively constant. This condition occurs for both the STATIC and ARC data sets. Table 5 summarizes the results. If the error is defined as a percentage of slant range, as is often the custom in manufacturer's literature for receivers such as these, the values for the ARC and STATIC data sets are strikingly similar. Figure 23 is a scatter plot of the actual error data

sets employed in these calculations. The dominance of the tangential or bearing error is readily apparent.

Table 5. Nautronix ATS Receiver Position Error

Maneuver	Num Fixes	Mean Range (m)	CEP66 (m)	Error as % of Range
ARC	283	300.8	1.85	0.62%
STATIC	354	216.5	1.34	0.62

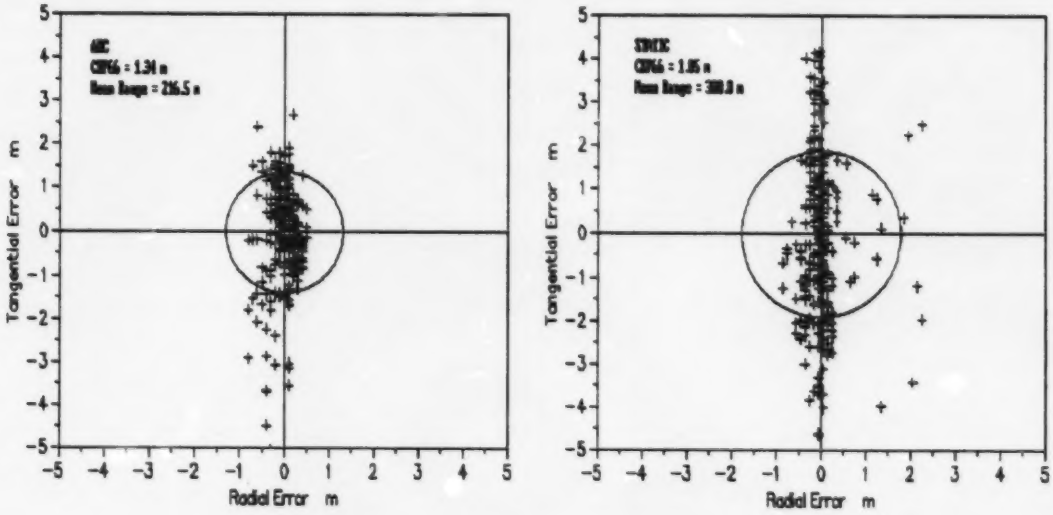


Figure 23. Nautronix ATS receiver range (radial) and bearing (tangential) error scatter plots for ARC and STATIC maneuvers.

10. Discussion

10.1 The Experimental Process

Both the DREP and the BIO experiments were intended to be rigorous comparative evaluations of acoustic USBS range/bearing receivers under conditions similar to those which would be encountered operationally. Two significant problems were encountered, the first relating to the geometry of the experiment and the second to the acoustic propagation conditions present during part of the trials. Their combined effect prevented the attainment of this goal. However, valuable quantitative and qualitative receiver performance information was obtained.

The range and bearing accuracies of the acoustic receivers were determined by comparing the position of a remote underwater acoustic source to that of an optical prism on the surface above it. Vertical separation is a necessity in order that each operate in the appropriate medium. However, their positions must be coincident in the horizontal plane for an accurate comparison to be made. No practical mounting or suspension system can achieve significant depth of the acoustic source without horizontal offsets of comparable magnitude to the errors being studied. This limits trials to modest depression angles at which USBS receivers do not, in general, perform at their best.

Because significant periods elapsed between some of the experiments, it is likely that environmental conditions such as background acoustic noise and propagation characteristics at the sites varied. The effect of these factors on the validity of the results is not easily quantified.

10.2 A Comparison of Range and Bearing Accuracy

Table 6 summarizes the receiver range and bearing errors after the various adjustments and editting procedures previously described have been implemented. The same information is depicted graphically in Figure 24. Hydrostar range error data is non-existant because a pinger was used. The same is true for the Trackpoint II RADIAL data. No ARC maneuver was performed for the Trackpoint II and no ROTATE maneuver was performed for the Hydrostar. The STATIC data for both the Trackpoint II and Nautronix ATS are probably reasonably free of errors introduced by the postulated offset between the optical and acoustic targets when the source was suspended by a line beneath a buoy. However, the PASS and ROTATE data sets are believed to be contaminated by this effect so they have been excluded from the computation of mean errors.

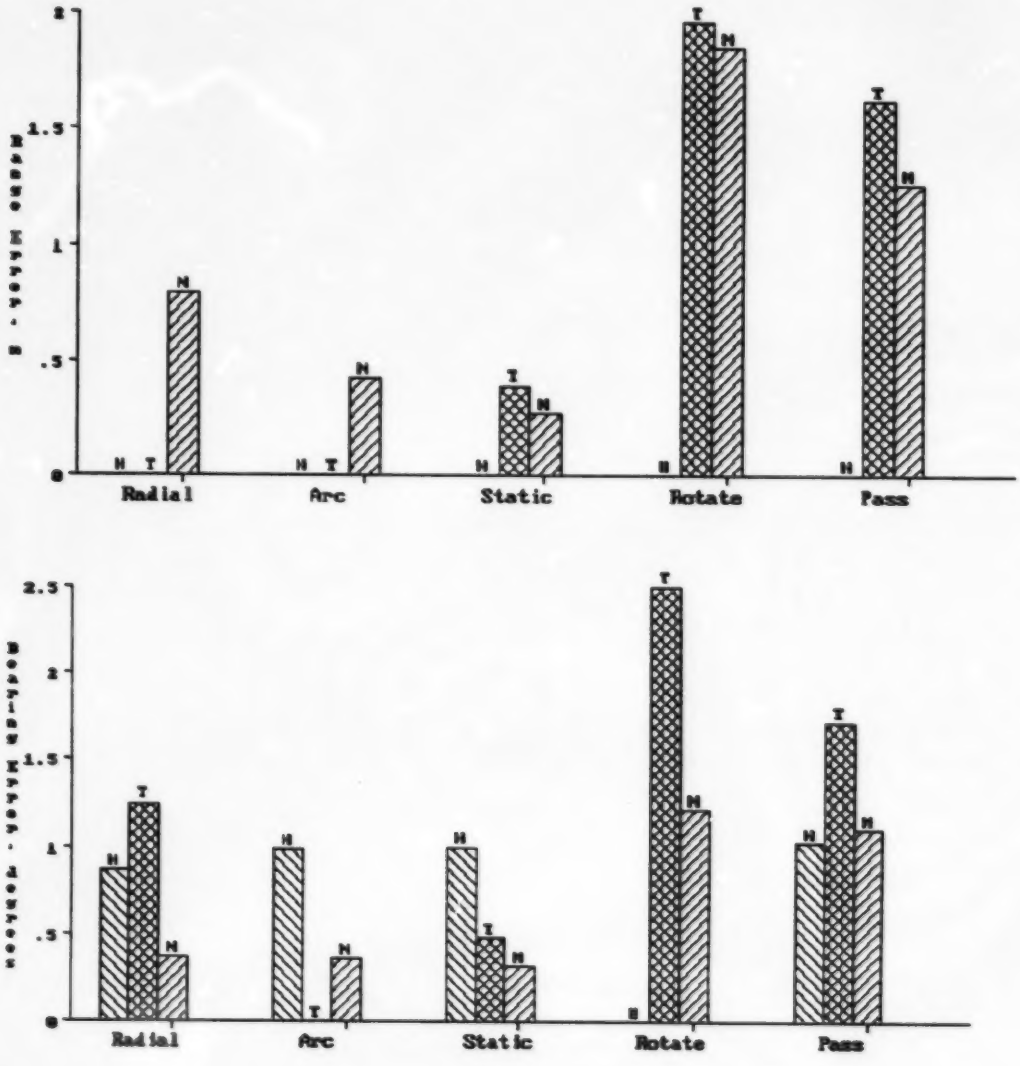


Figure 24. Standard deviation of the range and bearing errors for the Hydrostar (H), Trackpoint II (T) and Nautronix ATS (N) receivers for each of the maneuvers performed.

Table 6. Range and Bearing Errors

Maneuver	Std. Dev. of Rng. Error			Std. Dev. of Bear. Error		
	Hydro	Trkpt	Nautr	Hydro	Trkpt	Nautr
RADIAL	-	-	0.79m	0.87°	1.25°	0.37°
ARC	-	-	0.42	0.99	-	0.36
STATIC	-	0.39m	0.27	1.00	0.48	0.32
mean	-	0.39	0.49	0.95	0.87	0.35
ROTATE	-	1.95	1.84	-	2.50	1.22
PASS	-	1.61	1.25	1.03	1.72	1.11

10.3 A Comparison of Successful Interrogation Rates

Typically, acoustic USBS receivers are used where there is relative motion between the target and receiver such as to position an ROV with respect to a support ship. Such applications require rapid update rates. Also, if rates are sufficiently high, effects of excessive ambient noise and fix-to-fix uncertainty can often be reduced through filtering. Therefore, the rate at which a receiver successfully communicates with and correctly positions a target is of considerable practical importance. Tests of the receivers described herein were done under very similar acoustic conditions. While these conditions were somewhat more ideal than would usually be encountered operationally, a comparison of the relative interrogation success rates is indicative of their relative ability to communicate with and track a target. Table 7 summarizes the performances observed during these trials. "Replies Received" represents the number of replies actually accepted and logged by the receiver. "Good Fixes" represents the number of fixes which were within +/-5° and, for the transponder sources, +/-5 m of the correct value. Both have been normalized to the maximum number which could have been received during the same period.

Table 7. Interrogation Success Rate

Receiver	Pinger		Transponder	
	Replies Received	Good Fixes	Replies Received	Good Fixes
Hydrostar	86%	85%	--	--
Nautronix ATS	--	--	67%	65%
Trackpoint II	92	73	93	93

When each receiver is used with the source specified by the manufacturer, that is, the Hydrostar with its pinger and the Nautronix ATS and Trackpoint II with their corresponding transponders, virtually all the replies received from the target

produce acceptable fixes. While the Trackpoint II appears to receive as many of the possible pinger fixes as it does with its transponder, significantly fewer produce acceptable position information. Perhaps its performance has been optimized for use with a transponder at the expense of pinger operation. The Nautronix ATS receiver detects substantially fewer replies from its transponder than does the Trackpoint II. This may be a consequence of the more complex acoustic signal encoding utilized by the former. Perhaps the merit of this feature would have been more apparent if the comparison between the receivers had been done in a noisier acoustic environment.

11. Conclusions

The operational accuracies of three USBS acoustic positioning range/bearing receivers, a Hydrostar, a Trackpoint II and a Nautronix ATS, were determined. An evaluation with the source and receiver at the same depth yielded satisfactory results. A second effort wherein the source was at some significant depth with respect to the receiving hydrophone produced unacceptable results. It is postulated that current drag on the line joining the source and the optical prism of the reference system on the surface caused one to be displaced with respect to the other. This offset caused systematic experimental errors of the same order of magnitude as the positioning errors being quantified.

The three receivers are basically similar in configuration and function. They are made up of three components: 1) an acoustic transceiver, a computer and video display contained within a single case with a front panel keypad for operator control; 2) an underwater unit incorporating a hydrophone and transmitting and receiving electronics; and 3) an interconnecting cable. Some systems incorporate a set of tilt sensors in the hydrophone case and others place them in a separate package referred to as a Vertical Reference Unit. All systems provide graphical outputs to remote displays and alpha-numeric information to digital logging devices. The Hydrostar graphics are monochromatic and of limited resolution. The other two receiver displays are full color and high resolution. The Nautronix ATS remote graphics displays can be configured differently from the master display whilst the remote displays of the other two can only mimic the master. The Nautronix ATS displays the position history of the target(s) being tracked whereas the Trackpoint II and Hydrostar only show the most recent valid position. The Hydrostar is the simplest to operate with very few operator selectable adjustments available. The Nautronix is the most complex with multiple layers of menus permitting control over a broad range of basic and optional features.

All three receivers operate in the 15 to 30 kHz frequency range. They are designed to track sources which are normally within 45° of the vertical although all had no problem tracking sources in the horizontal plane to ranges well in excess of 1000 m in shallow water. The Trackpoint II and Hydrostar produced acceptable fixes for about 90% of the attempted interrogations. The Nautronix ATS on the other hand only did so about 67% of the time.

The experiments described herein indicate that the bearing accuracy of the Hydrostar receiver in a horizontal geometry is $+/-0.95^{\circ}$. This appears to be consistent with the manufacturer's specification of $+/-0.40^{\circ}$ at 50% offset, $+/-0.72^{\circ}$ at 100% offset and somewhat poorer accuracy at near horizontal geometry where offset is the ratio of horizontal range to source depth. Infrequently, the receiver will produce a single bearing measurement or spike which is clearly incorrect. Also, it will very infrequently produce a series of bearings which are an

integral multiple of 120° in error. The receiver exhibits a bearing-dependent bearing error which does not appear to change with time or hydrophone mounting arrangement. The accuracy of the bearing measurements can be improved if a correction for this error is applied. No range-dependent bearing errors were detected.

The Trackpoint II receiver tested was an early version which lacked modifications which would have improved its performance. It was found to have a range measurement accuracy of 0.39 m and a bearing accuracy of +/-0.87° when the source was in the same plane as the hydrophone. The range accuracy is better than the manufacturer specifies. The bearing accuracy is very similar to that of the Hydrostar receiver and about three times worse than that specified by the manufacturer but that may be because the latter is defined for a near vertical geometry. Unique to this receiver are the visual and audible indicators of acoustic performance which provide the operator with a convenient and efficient method of monitoring receiver performance. No range-dependent bearing errors were noted. Insufficient data were collected to determine whether or not the receiver had a bearing-dependent bearing error similar to that observed with the Hydrostar. Very few fixes accepted and displayed by the receiver are totally erroneous. However, under poor propagation conditions the receiver appears to accept multipath signals and the error bounds increase.

For the most part, the Nautronix ATS receiver produced useful position data. However, there were significant periods when the indicated range and/or bearing varied in a consistent but totally incorrect manner. No range-dependent errors were detected but, like the Hydrostar receiver, the Nautronix ATS exhibited a bearing-dependent bearing error which could be eliminated through application of a calibration correction. The receiver was found to have a range measurement accuracy of 0.49 m which is very similar to that of the Trackpoint II and better than that specified by the manufacturer. The bearing accuracy of the Nautronix ATS with a horizontal source/receiver geometry is +/-0.35° which is about two and a half times better than the Trackpoint II and Hydrostar. While it is poorer than that specified by the manufacturer, this discrepancy may be the consequence of different source/receiver geometries being employed when quantifying the error. It has a positioning accuracy (CEP66 radius) of 0.62% of slant range when the source is at the same depth as the receiver.

References

Anon., 1989. Trackpoint II improved, International Underwater System Design, Vol. 11 (6), pp. 17, November.

Anon., 1990. Trackpoint II wins performance trials, ORE Trackpoint II News, No. 9, pp. 1, May.

Beaton, K., 1983. Hydrostar: an acoustic positioning system for ROV's, International Underwater System Design, pp. 25-28, Dec.

Harre, I., 1990. Accuracy evaluation of polar positioning systems taking Polarfix as an example, Int. Hyd. Rev., LXVII (1), pp. 37-59.

McKeown, D. L., 1984. O.R.E. Trackpoint acoustic range/bearing receiver evaluation, Can. Tech. Rep. Hydrogr. Ocean Sci. No. 47: 37 p.

McKeown, D. L., 1990. Bearing measurement with the Honeywell Hydrostar acoustic positioning receiver, Proc. Intervention/ROV '90 Conf., Vancouver, June 25-27, pp. 257-261.

Selman, B., 1985. The Trackpoint II acoustic navigation system, International Underwater System Design, Vol. 7 (2), pp. 29-30, 37, March.

Selman, B., 1989. Letter to the editor, SeaTechnology, Vol. 30 (6), pp. 48, June.

Selman, B., 1990. Ferranti-ORE, private communication, June 19.

Trenholm, B., 1990, private communication, Defence Research Establishment Atlantic, Dartmouth, N.S., Oct. 3.

Zaknich, A., 1989. ATS: a new generation acoustic positioning system, SeaTechnology, Vol. 30 (3), pp. 25, 27-28, 30, 32, March.